Studies on Low-cost Wireless Information Networks Over Existing Infrastructural Facilities in Rural Area

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Agussalim

Preface

Over the past decades, the evolution of the Internet has had a deep influence on almost all aspects of human life. The number of Internet users has continued to grow, and human life has become ever more dependent on the Internet and information technology; however, the availability of Internet remains scarce in some areas of developing regions due to a lack of communication network infrastructure. In such areas, such as rural areas and remote islands, the construction of new infrastructure is not cost effective because of geographical considerations or because the small and scattered population provides few potential users.

This dissertation reports two typical scenarios and proposes a low-cost solution for information networking using existing infrastructure rather than creating new infrastructure from scratch. This can be achieved by (i) stationary multi-hop wireless networking on static facilities and (ii) store-carry-forward-based ad-hoc multi-hop wireless networking using vehicle transportation infrastructure. These networks offer promising solutions for data communications in rural areas by expanding the coverage area and overcoming the limitations of standard communication systems in these environments.

Wireless multi-hop networks have been developed to provide connectivity without the need to install area-wide wired links. These are of practical importance because of their lower cost, rapid deployment, and flexibility compared with wired line networks. They are suitable for applications wherein a normal communications network infrastructure is unavailable, such as agricultural monitoring, emergency response systems, and electrical facility monitoring. Delay/disruption-tolerant networks (DTNs) have been used widely in such applications and offer a promising solution in challenging environments where end-to-end connectivity is not possible and traditional networks fail. Messages are delivered from a source node to a destination node via a store-carry-forward routing.

In Section 3, a real facility monitoring scenario for stationary multi-hop wireless networking on static facilities is discussed. This comprises a series of stationary surveillance sensors arranged in tandem along a road, river, or power-transmission tower network. Stationary sensor nodes periodically generate monitoring data at each time-slot T (in ms or s). This data is sent to a single central management server via one of the gateways at the edges. We propose a framework for message transmission scheduling on a tandem multi-hop transmission network using lossy wireless links, including a simple XOR network coding-based scheme for proactive message transmission under the proposed static time-slot assignment.

Sections 4-6 introduce real-life scenarios for large file delivery across islands by store-carry-forward-based ad-hoc multi-hop wireless networking using vehicle transportation infrastructure. In these scenarios, the source and destination are located on different islands connected via ferry boats. Messages are delivered from the large island to the small island and local vehicles (buses and cars) act as relay nodes on each island. After analyzing the performance of several routing protocols and comparing the advantages and disadvantages of existing protocols, we propose an improved routing protocol for our island scenario. This dissertation is organized as follows.

First, in Chapter 1, we present the design requirements for providing wireless information networks to rural areas. Furthermore, the challenges in the installation of DTNs and static multi-hop wireless networks are discussed.

Second, in Chapter 2, we present a survey of related work and give the background to this research, which includes static multi-hop wireless networks, Delay Tolerant Network (DTN), and communication challenge in rural areas.

Third, in Chapter 3, we introduce a framework for message transmission scheduling using a tandem multi-hop transmission model with lossy unreliable wireless links, where each of the N nodes periodically generates a message every T time-slots. The framework comprises (i) a static global time-slot assignment over all links and (ii) message selection for transmission in an assigned time-slot on each link. Next, we develop an analytical derivation for (i) and a message selection system for (ii) that includes redundant transmission with simple XOR network coding-based proactive recovery. Simulation results show that the probability of successful delivery in the proposed framework is comparable to that of ACK-based reactive recovery schemes. This suggests the effectiveness of our simple approach.

Fourth, in Chapter 4 compares DTN routing protocols (Epidemic, MaxProp, ProphetV2, and Direct Oracle) in realistic scenarios while varying the number of created messages (message generation rate), message size, transmission range, and transmission speed in scenarios that closely model real-world environments in developing regions. The performance is evaluated based on the total number of messages, delivery probability, and the overhead ratio, and the impact of the scenarios on the evaluation result is analyzed.

Fifth, in Chapter 5 introduces a DTN routing protocol. We call this spray- and hop-distance-based with remaining-TTL consideration (SNHD-TTL). It integrates three features: (1) binary spray, (2) hop-distance-based forwarding, and (3) remaining TTL consideration message scheduling based on global knowledge about the network. Our goal was to improve the probability of successful delivery under congestion, particularly in our island scenario. Evaluation was performed through simulation-based comparison with other popular protocols, using Epidemic as a baseline and PRoPHETv2, which performed well in a previous study using the island scenario.

Finally, in Chapter 6, we propose the adaptive-spray and hop distance-based protocol (A-SnHD), which is a modification of our protocol proposed in [1]. A-SnHD switches between two phases on each island; binary-spray forwarding is used when a message reaches the island and hop distance-based forwarding is used in a strict manner to prevent transmission to the wrong island. ONE simulator-based performance evaluation of multi-island scenarios was used to model a real environment in Indonesia. The results show that, although it is simple, A-SnHD expands the total number of generated messages while reducing the overhead ratio, compared with EP as a basic protocol and PV2 as a sophisticated protocol.

In closing, I hope that the presented dissertation will be helpful for further studies in this field.

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Agussalim

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Chapter 1

Introduction

1.1 Information networks in rural area

Internet technology has evolved as a major need for human life aspect. It transforms the humanity into the information age in which can provide knowledge instantly. People can study through the Internet, access the digital content, and collaborate with college remotely in all around the world. Refer to the world internet statistic [10], 46.5% population in the world enjoying Internet facilities, the higher region is in the North America as 87.9%, Europe as 73.5%, and Oceania/Australia as 73.3%. On the other hand, as a developing region, Asia and Africa has a lower population that connected to the Internet, as 40.2% and 28.6% respectively.

Some areas in developing region are classified by a rural area due it lack of supporting infrastructure (road and electricity) and geographical condition (remote island). These are the reason why the penetration of Internet in the developing regions is very low compared with the developed regions. Furthermore, the cost to provide Internet communication in a rural area became very expensive as the user is very small. The location of some area with the lack of proper roads or located on the remote island that makes them difficult to reach affected the instability and deficiency infrastructure, maintenance and operational costs is

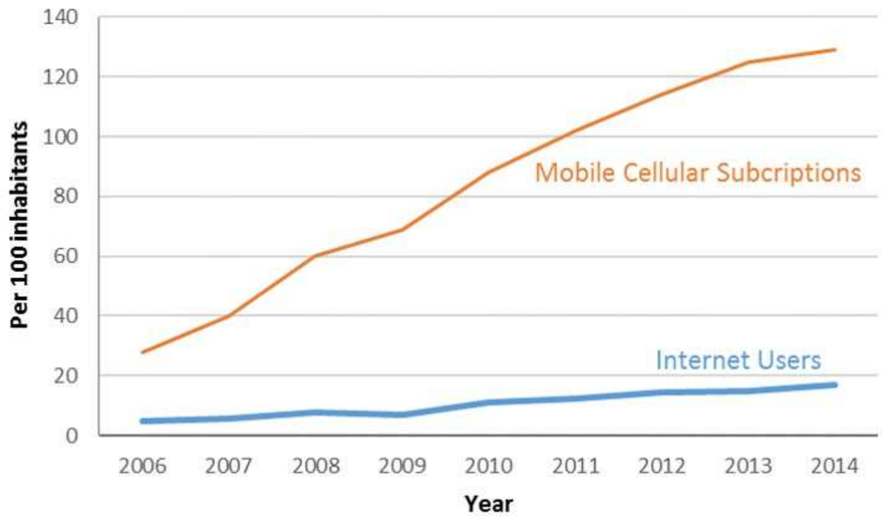


Figure 1.1: Indonesian Internet penetration and mobile subscriptions per 100 inhabitants

also expensive.

As the largest archipelago country in the world, Indonesia has many islands among which some are small, some are remote, and some do not have a high-speed data communication infrastructure due to its high-cost for deployment. Figure 1.1 shows Indonesian Internet user and mobile subscriptions per 100 inhabitants. In comparison with Mobile-cellular telephone subscriptions, the increasing of Internet penetration in Indonesia is relatively low, at the end of 2014, Internet user was 17 million more [11]. This indicated that some cellular communication infrastructure does not provide sufficient data communications.

This dissertation proposed two solutions to provide low-cost communications in the rural area. By considered to use some existing infrastructure over the region as a backbone of wireless information networking for the rural area. Depending on cases (conditions, applications) as follows: (i) Stationary multi-hop wireless networking on static facilities; (ii) store-carry-and-forward-based ad-hoc multi-hop wireless networking on the vehicle. These networks may provide a promising solution for data communication in rural areas by ex-

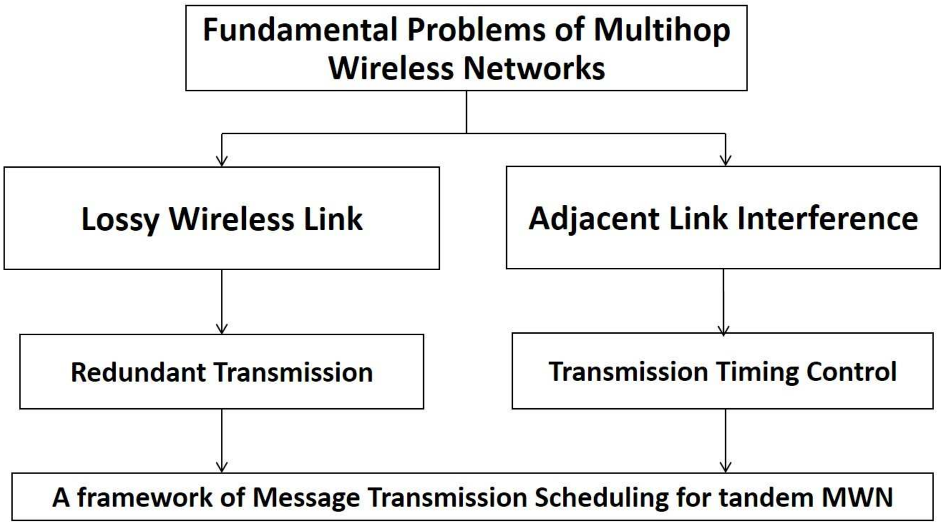


Figure 1.2: Fundamental problem of static wireless networks

pand the coverage area and tackle the limitation of current network technology that could not operate in all environments.

1.2 Challenge problems in stationary multi-hop wireless networking

Multi-hop wireless networks consist of multiple wireless nodes that collaborate to provide communication between source and destination. They are of practical importance due to their lower cost, rapid deployment, and flexibility compared with wired networks in connecting or covering nodes in an area where single-hop wireless networking is not sufficient to work. Moreover, transmission over multiple "short" links might require less transmission power and energy than over "long" links. A static (stationary) multi-hop wireless network has considered in various applications. Among such applications, wireless sensor networks are one of emerging technology that can cover a large geographic area and provide connectivity

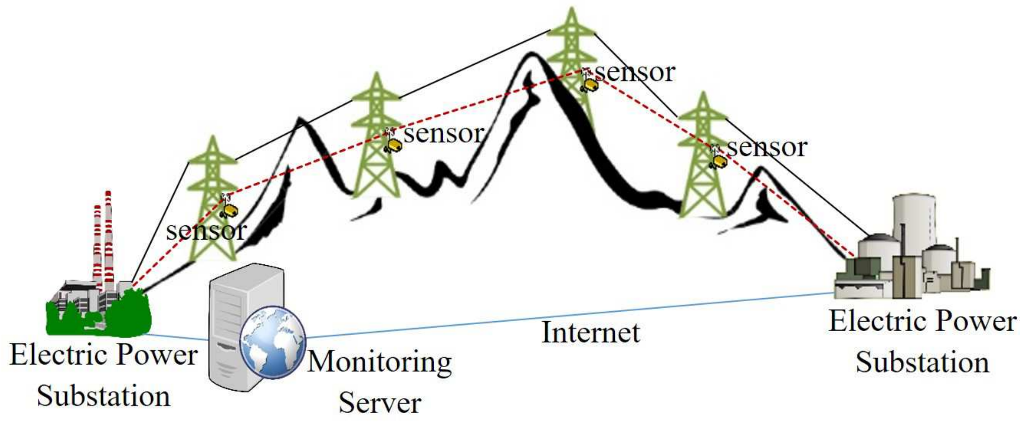


Figure 1.3: Real-world Facility Monitoring Scenario

without physical access to every sensor node.

Due to the nature of wireless multihop radio communications. It faces some problems: lossy unreliable wireless radio links; and conflicts (interferences) among simultaneous transmissions on adjacent links (or links within an interference range) using the same radio frequency channels [31], especially in using a non-directional (omnidirectional) antenna. Those problems significantly impact the performance of static multi-hop wireless networks as shown in Figure 1.2.

We consider 2-gateway tandem multi-hop networks with lossy unreliable wireless links, which can be seen in facility monitoring scenarios where multiple stationary nodes (sensors that can relay messages) arranged along a road, river, or power transmission tower network. Those stationary sensor nodes generate monitoring data periodically every T [time-slot, e.g., msec or sec] that send to a single central management server via one of the gateways at the both edges. Although a whole network structure is stable, messages can be exchanged only with two neighbour nodes by a limited distance, low-cost and lossy unreliable wireless link, as shown in Figure 1.3.

In this study, we proposed message transmission scheduling system that consists: (i) a static global time-slot assignment for each link is considered to avoid unnecessary interferences to maximize the probability successful of all N generated messages to reach a gateway within each T duration; (ii) a message selection include network coding is adopted to recover lost messages due lossy unreliable wireless radio links. Our objective is to find good global static slot assignment using mathematical optimization problem and a good message selection for a given slot assignment than can maximize the probability that generated messages from all nodes successfully delivered to either one of gateways in T time-slots ("the success delivery probability").

1.3 Challenge problems in store-carry-and-forward-based ad-hoc multihop wireless networking on vehicle networks

Delay Tolerant Network (DTN) came from the study of how to provide the connection in end-to-end connectivity environment is not normal. Its enables communication in the environment with a cross-connectivity, unstable and large delay time, high error rate, sparse mobile ad-hoc networks and other challenged environments where the traditional networking failed, and new routing and application protocols are required. Message are delivered from source node to a destination node via store-carry-and-forward-based routing. A source node or relay node store message in buffer storage and carries them according to its movement. These messages forwarded when it encountered other node based on predefined criteria until it delivered to a destination node by multiple hops.

Transferring messages across DTN networks is a challenging problem, as such algorithm development has primarily concerned with providing maximum throughput and minimal delays while typically assuming unlimited storage and transfer bandwidth. The most primitive replication-based forwarding algorithm referred to as epidemic forwarding [7], which repli-

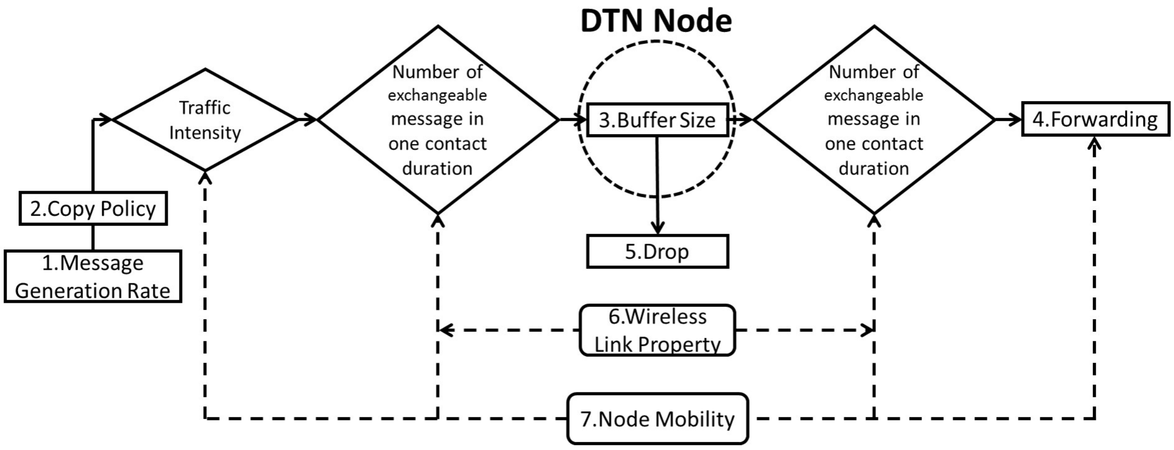


Figure 1.4: Performance Factor of DTN

cates copies of a message to all nodes in the network this method is excessive and therefore not scalable. In order to address the number of redundant copies produced by epidemic forwarding, algorithms have emerged that forward a number of copies to a subset of encountered nodes. Past experience with DTN routes and application protocols shown their performance is highly dependent on the underlying mobility and node characteristics.

As shown in Figure 1.4, there are seven factors that influences performance of DTN: First is message generation rate, include message size, the number of generated messages, and the location of source and destination of messages; second is the limitation of the number of message copies that spread in the network (copy policies), it consists of single, limited (deterministic and probabilistic), and unlimited; third is buffer size, this indicate the occupancy of node to store the message during message delivery process; fourth is forwarding that consists of message selection and sending order (scheduling), message selection is a rule for forwarding message to another node, it consists of Direct delivery, Always, Context, History, Social, sending order is a rule in the message queue, which message will be selected first for forwarding to other nodes i.e. (FIFO and random); fifth is drop message, this process will delete the message from buffer storage depending on two reasons; (1) to give free space

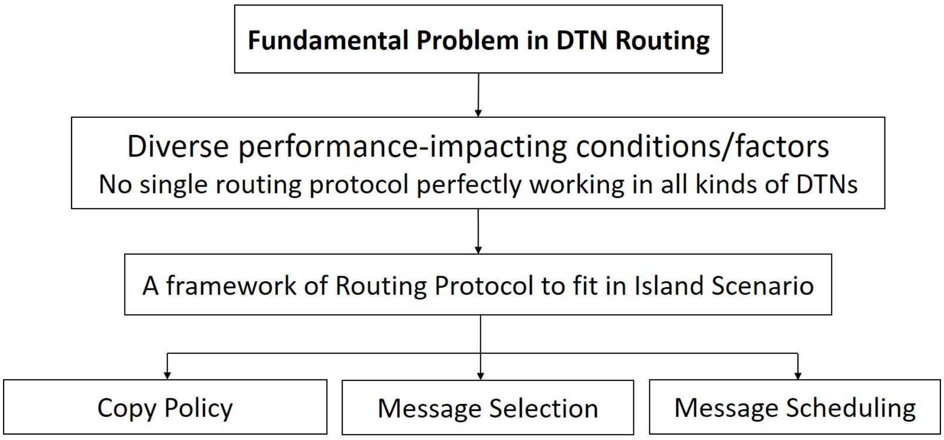


Figure 1.5: Fundamental problem of routing protocol in DTN

for the new incoming message when buffer storage is full, (2) the TTL value of the message is same or lower than zero, and the other method is based on drop policy (buffer management) algorithm; sixth is wireless link property that consists of Xdata rate and Xdata range that affect to the number of exchange message in one contact duration; and seventh is node mobility, the movement pattern of DTNs node, it affect contact interval and contact duration. Traffic intensity, is affected by message generation rate, copy policy and node mobility.

The main challenge in DTN research is routing protocol development. In a few decades, there are many proposed routing protocols within the DTN community. Over the last decade, DTN research community has been developing various store-carry-and-forward routing protocols. The major differences among these protocols rely on the information to make the routing decision (e.g., history of node encounter, global information about the network, location information, etc.), and message dropping and replication strategy (e.g., limitation of the number of copies per message). Unfortunately, each routing protocol has its advantage in a particular scenario, and no routing protocol can perfectly work for all kinds of challenged environments. Figure 1.5 show the fundamental problem of routing protocol development in DTN.

In [1], we have analyzed the performance of different store-carry-forward routing protocols in DTN (Epidemic, Direct Oracle (our proposed routing), MaxProp, and ProphetV2) to find their advantages and disadvantages by considered a scenario as close as possible to a real-world practical situation (i.e., Island Scenario), under the various number of created messages, messages size, transmit range and transmit speed, using three performance metrics; total size of delivery messages, delivery probability, and overhead ratio. Messages delivered from the large island to the small island, vehicles (car, and bus) employed as a relay node on each island, and a ferryboat connects two islands via station on each island. While our investigation is in the preliminary stage, our observations revealed complex dependencies of performance on routing protocols, and implies there is no single best routing protocol in the considered scenario.

Based on investigation results in [1], we need a framework of routing protocol to fit in island scenario that consists of message selection and sending order (scheduling) with message copy limitation. We proposed a DTN routing protocol by considering bottleneck on communication between ferryboat and station at each island, called spray- and hop-distance-based routing with TTL consideration (SNHD-TTL). It integrates three features: (1) binary spray; (2) hop-distance-based forwarding; and (3) remaining TTL consideration for message scheduling based on global knowledge regarding the network [2]. We also evaluate our proposed protocol by comparing it with other popular protocols, namely Epidemic as a baseline and PRoPHETv2 that performs well according to our previous study regarding the island scenario. Our simulation results show that SNHD-TTL is able to outperform the other routing protocols, drastically reducing overhead and, at the same time, significantly increasing the total size (amount) of delivered messages.

In [3], we adapted our previously proposed routing protocol to the multiple-island scenarios with some modification and evaluate its effectiveness in two cases of delivery direction. In this newly proposed version, namely adaptive-spray and hop-distance protocol (A-SnHD), the binary-spray forwarding is repeatedly used when a message reaches each island, and the hop distance-based forwarding is strictly used to prevent unnecessary transmission to wrong islands. Simulation results show that A-SnHD outperforms Epidemic and PRoPHETV2 in terms of the total size of delivered messages and the overhead ratio.

1.4 Outline of this dissertation

This dissertation consists of seven chapters, each chapter is organized as follows: Chapter 1 is an introduction. It shows application and challenge of multi-hop wireless networks. Chapter 2 presents related work of this research, especially about the background of multi-hop wireless networks and Delay Tolerant Networks.

Chapter 3 shows the proposed framework for message transmission scheduling on tandem multi-hop transmission model with lossy unreliable wireless links, where each of N nodes periodically generates a message every T time-slots. Such a model is of practical importance, e.g., in low-cost large-scale sensor networks in the wild. Each message can be transmitted from a node to an adjacent within each single time-slot, and should be relayed in a store-wait-and-forward manner from its source node to one of gateways at the edges of the tandem within T time-slots. The framework consists: (i) a static global time-slot assignment over all links; and (ii) message selection for transmission in an assigned time-slot on each link. We develop an analytical derivation for (i) and a message selection including redundant transmission with a simple XOR network coding-based proactive recovery for (ii).

Chapter 4 shows the comparison of DTN routing protocols in realistic scenarios, using the ONE Simulator, we investigate four SCF-based DTN routing protocols (Epidemic, MaxProp, ProphetV2, and Direct Oracle) by varying the number of created messages (message generating rate), the message size, the transmission range, and the transmission speed in scenarios that closely resemble the real-world practical situations that arise in developing regions. A performance evaluation based on the total size of delivery messages, delivery probability and overhead ratio is conducted, and the impact of the scenarios on the evaluation result is analyzed. While this investigation is in the preliminary stage, our observations reveal complex dependencies in performance on both scenario parameters and routing protocols, which motivate and will be essentially utilized to develop a means to adjust protocols dynamically by estimating and reflecting scenario parameters.

Chapter 5 shows the proposed of DTN routing protocol, called spray- and hop-distance-based with remaining-TTL consideration (SNHD-TTL) which integrates three features: (1) binary spray; (2) hop-distance-based forwarding; and (3) node location dependent remaining-TTL message scheduling, aiming at a better delivery probability in congestion especially in the island scenario we consider. We evaluate it by simulation-based comparison with other popular protocols, namely Epidemic as a baseline and PRoPHETv2 that performs well according to our previous study regarding the island scenario. Our simulation results show that SNHD-TTL is able to outperform the other routing protocols, significantly reducing overhead, and at the same time, increasing the total size (amount) of delivered messages.

Chapter 6, we consider DTN message delivery scenarios over multiple islands where four islands are connected by ferry boats shuttling between ferry terminals (i.e., stations). In our scenarios, the source and destination nodes are stationary and located in marginal islands, and a central island acts as a relay island. Messages are relayed by cars and buses in each island and by ferries between islands. we develop Adaptive-spray and hop-distance protocol (A-SnHD), by modifying a simple routing protocol, Spray and hop-distance protocol (SNHD), proposed in our previous work [2]. The modification is done in two functions. One is the binary-spray forwarding in which the copy limit (L) of each message is reset at the ingress point of each island (i.e., the ferry station) to maintain the number of message copies on each island. The other is the hop distance-based forwarding in which more strict comparison of the encountered node's hop-distance from the message's destination node is used to prevent unnecessary transmission to a wrong island during message delivery.

Chapter 7 summarize the dissertation.

Chapter 2

Related Work

2.1 Static multi-hop wireless networks

Multi-hop wireless networks are referred to multiple wireless nodes collaborate to provide communication between source and destination in the different area. They are of practical importance due to their lower cost, rapid deployment, and flexibility compared with wired networks in connecting or covering nodes in an area where single-hop wireless networking is not sufficient to work. As we discussed in the previous section, there are two fundamental issues in multi-hop wireless networks. Recovery of lost messages due lossy unreliable wireless radio links can be considered either in a reactive manner, i.e., ACK and NACK-based retransmission (ARQ), or in a proactive manner, i.e., message-level forward erasure correction (FEC) and bit-level forward error correction. On the other hand, two types of Media Access Control (MAC) schemes can be considered to avoid/reduce simultaneous transmission conflictions, the contention-based such as CSMA/CA and the scheduling-based such as Time Division Media Access (TDMA). For the first issue, an FEC-based transmission was proposed in [32], [33], it achieved reliability by adding redundancy to transmitted packets. Then in [34] and [38] proposed XOR-based network coding to the loss recovery of reliable broadcast transmission in wireless networks. He et al. [35], proposed BPR, a Bit-level Packet Recovery scheme in WSNs. In BPR, if a packet corrupted for two times, instead of a request the whole packet, the receiver compares these two corrupted copies of the packets and determines which bit(s) should be re-transmitted. Sagduyu et al. [39] implemented network coding in tandem network case, they considered the problem of network coding in wireless queuing networks with tandem topology and evaluated throughput and energy costs in cooperative and non-cooperative equilibrium. For the second issue. In earlier work of TDMA scheduling, it is based on distributed implementation, i.e., [40] proposed a distributed implementation of RAND, a randomized time slot scheduling algorithm, called DRAND. Otherwise, the shortest schedules are proposed in [41], which introduced two centralized algorithms: one based on direct scheduling of the nodes or node-based scheduling, and the other based on scheduling the levels in the routing tree before scheduling the nodes or level-based scheduling. Madan et al. [36] restricted the link schedules to the class of interference-free TDMA schedules, they formulated the optimization problem as a mixed integer convex program. Similar work with [37], they build a nonlinear cross-layer optimization model involving the network, MAC, and physical layers, which aims at reducing the overall energy consumption by the solved interference-free problem, then proposed an algorithm for deriving the TDMA schedules, utilizing the slot reuse concept to achieve minimum TDMA frame length. Zeng et al. [42] proposed a new scheduling algorithm based on the collaboration of nodes to resolve the slot collision when nodes try to assign slots to them. The collaboration consisted of three phases: REQ, REPLY, and ACK are used to guarantee the interference-aware slot assignment during each round. Our approach is as follows. For link error recovery, since each network node is assumed to be low cost with little computational power and low electric power consumption, we consider no complicated physical layer functions (adaptive moderation, intelligent power control, etc.) and no ACK-based reactive recovery. Instead, we adopt a simple XOR network coding-based proactive lost message recovery on lossy unreliable wireless links. For interference avoidance, we utilize a simple TDMA by a centralized (global) control for time-slot assignment focusing on tandem static multi-hop transmission model. Since the message generation rate at each node assumed to be stable, a static TDMA-based approach can be efficient. On a simple tandem model instead of a general mesh model, we can apply a mathematical optimization problem to formulate a static “optimal” global time-slot assignment over all links.

2.2 Delay Tolerant Network (DTN)

Delay Tolerant Networks (DTN) enables communications in an environment with a cross-connectivity, variable or large time delay, high levels error, sparse mobile ad-hoc networks and other challenged environments where the traditional networking failed, and new routing and application protocols required. It is more suitable to applied in remote areas. DTN support mobility and use of limited resources from the development of wireless communication devices. The main challenge in DTN research is routing protocol development includes forwarding and message scheduling. DTN implement the store-carry-forward (SCF) paradigm for message delivery when an end-to-end connection may never reached. SCF is well suited for use in vehicular networks (e.g., cars, buses, and boats) for message-relaying services by moving around a network to collect messages from source nodes and/or to deliver messages to destination nodes as shown in deployments such as UMassDieselNet [14].

2.2.1 Forwarding in DTN

The forwarding policy determines which messages should be forwarded when two nodes encounter one another. If the number of messages that can be transmitted within a contact duration is enough (i.e., the transmission bandwidth is large enough and the contact length is long enough). And the number of messages that can store in a node is sufficient, the simplest, fastest, and most reliable way to deliver messages to the destination is Epidemic routing (EP) [7]. In which messages are spread to all encountered nodes of the network to maximize the chance of reaching the destination. When two nodes encounter one another, they exchange a list of message IDs and compare those IDs to determine which message is not already in storage in the other node; next, those messages are forwarded to the other node; however, its resource consumption increases significantly as the number of message copies increases. Several studies have focused on trying to reduce resource consumption [6-9]; these studies introduced forwarding decisions for controlled flooding, e.g., history-based or utility-based routing; results of these studies have shown good performance in comparison with simple flooding. One of the most well-known protocols in this category is the probabilistic routing protocol using history of encounters and transitivity (PRoPHET)[9]. One of other sophisticated schemes is MaxProp presented in [14], in which a path cost is computed based on the meeting probability of each hop along the destination, and the shortest cost path is selected. Note that our previous work[1] showed that PRoPHETv2 (PV2) [13] outperformed MaxProp in the island scenario.

In another approach, e.g., SCAR [12], and Spray and Wait [8], a limited number of message copies are implemented in each algorithm to deliver a message. Spray and Wait (SNW) routing [8] use the capabilities of EP for fast message forwarding and reliability of direct transmission, with a limitation of message copies (i.e., controlled flooding). The approach here consists of the following two phases: (1) a spray phase, described in Section 3-1 and (2) the wait phase in which a relay node moves and waits for an opportunity to meet directly up with the destination. Since the wait phase does not perform well in some scenarios, including our island scenario, Spray and Focus routing (SNF) [8] has been proposed to address this problem; the difference between SNF and SNW is that after the spray phase, SNF uses utility-based forwarding to improve delivery probability.

Spray based protocol attracted many researchers to improve its performance, in [16] spray protocol improved with probability Choice (SWPC), where continuous encounter time is used to describe the encounter opportunity. In [17] E. Bulut et al. propose a novel spraying algorithm in which the number of message copies in the network depends on the urgency of meeting the expected delivery delay for that message. The main objective of this protocol is to give a chance to early delivery with a small number of copies sprayed in the network. The combination of Spray and Wait [8] and PRoPHET [9] is proposed in [19] which calculates the number of message copies to be forwarded based on the performance of receiver node in spray phase and in wait phase the waiting node uses history of encounters and transitivity of transmission.

In [48] a DTN routing algorithm named R-ASW (Relay-probability-based Adaptive Spray and Wait) has proposed in which the performance of the receiver node is used to determine whether forward a message to an encountered node and calculate the allowable number of message copies to forwarded. Reference [49] proposed an improved spray and wait routing based on the delivery probability that developed in the PRoPHETV2 routing protocol. Ababou et.al. [50] proposed a new strategy that optimizes the routing in Spray and wait using the information on paths traversed by the messages before arriving at their destination.

As another example, You et al. proposed a hop-count-based heuristic routing protocol for mobile DTNs, which calculates heuristic estimations based on hop count information [15]. In particular, they use a slide-window mechanism and dynamically update the average hop count matrix. Forwarding a message to encountered nodes nearer to its destination (i.e., at a shorter distance) is one of the basic approaches; however, a critical issue is how distance to the destination is defined and estimated (e.g., expected number of hops, expected time, expected success probability, etc.). In this dissertation, while more sophisticated schemes have studied and proposed, we adopt the binary spray protocol, with a simple hop-distance-based forwarding approach, in Chapter 5. The modification of our proposed method in Chapter 5 with the binary spray but its copy limit (L) can be reset depending on message location described later in Chapter 6.

2.2.2 Buffer management

In store-carry-forward paradigm, when the next hop is not available for the current node to forward a message, the node will store the message to its buffer until it gets a communications opportunity with the other node to forward this message. There are two kinds of buffer management policies: how to select messages to be dropped from the buffer storage when the buffer storage is full, and how to select messages to be sent to a contacted node (i.e., scheduling) in a limited duration of contact with a limited transmission bandwidth. Zhang et al. studied the utilization of traditional buffer management policies, such as drop front (DF) and drop tail (DT); they concluded that the DF policy outperforms DT [22]. Fathima and Wahibanu proposed a buffer management scheme with different queues handling messages at different priorities; when a buffer is full, a message on a low-priority queue is dropped first to create space for a new message [20]. Most Forwarded (MOFO) [23] proposed to increase the efficiency of message replication, it requires that routing agents running on nodes keep track of the number of times a node forwards each message. J. F. Naves et al. [24] explored a similar idea. Who proposed Less Probable Sprayed (LPS) and Least Recently Forwarded (LRF), LPS uses the message delivery probability and estimates the number of replicas already disseminated to decide which message to drop. LRF drops the least recently forwarded message based on the assumption that message not forwarded over a period of time have already reached next several hops. A. Elwhishi et al. [25] proposed a new message scheduling framework for epidemic and two-hop forwarding routing in DTNs, it incorporates a suite of novel mechanisms for network states estimation and utility derivation, such that a node can obtain the priority of each message to be dropped in case of the full buffer. Krifa et al. proposed sophisticated buffer management schemes called global knowledge-based drop and history-based drop [21]. These approaches use statistical learning to approximate global knowledge, estimating the number of copies of a message, the authors considered the remaining TTL and developed an optimal joint scheduling and buffer management based on estimated necessary parameters using locally collected statistics by assuming homogeneous and simply modeled mobility. Another integrated buffer management proposed in [26], based on statistics and analysis of the state of the messages, and considering the delivery history of the node and location information, combined with the relevant information from mutual learning between nodes. Based on the several strategies above, in Chapter 5 we propose a simple but practical node location dependent remaining-TTL message scheduling that utilizes the global knowledge about statistics of message delivery time in each closed area, i.e., island, with the remaining TTL value of each message.

2.3 Communication challenge in rural areas

Provide communication in the rural area of developing country is a challenging problem for the next generation network development. Many factor as the reason why this task was difficult to implement. The first is the geographical problem, some of the rural area located in which the lack of proper road or located on the remote island. Another issue is the availability of power infrastructure, the instability and deficiency infrastructure, high maintenance and operational costs. Moreover, in some country, the cost of the bandwidth is expensive through cellular and satellite coverage in the rural area.

Several researcher has been proposed alternative communication for the rural area by employing DTN. Khattak F. U. et.al., [43] introduced the role of DTNs for providing delay tolerant services to the countryside. Then proposed a modifications architecture to increase the efficiency of DTN. In reference [44], authors suggested a delay tolerant network architecture for content distribution, that recognizes content objects as first class entities cacheable at different nodes in the network, and uses an always-on control channel on GPRS/EDGE connections to assist in the routing of data. Galati A, et.al, offered DTN as a technology that is uniquely suited to the challenge of providing network access to people in rural areas environments. They introduced DTN as the micro-franchise model to test both the technological and economic viability of this new technology. This work presented in an ongoing project that provides communities in rural South Africa with cinema experience by training micro-entrepreneurs in the operation of a DTN-enabled micro-franchise [45]. Reference [47] introduced Goose, a distributed SNS for developing regions in which utilized both the limited GSM coverage and Delay Tolerant Networking (DTN) technologies running on mobile phones to enable social information exchange between members of a community even when cellular data coverage is not available.

Then the other type of communication in rural areas was introduced by [47], the author proposed VillageCell, it relies on software defined radios and open source solutions to provide free local and cheap long-distance communication for the remote region. Then in [46], presented design methodology to provide network connectivity from a landline node in the rural area at very low cost, this work is an approach for planning a suitable wireless mesh network for the rural area.

Our works are also provided low-cost wireless information networks over existing infrastructure facility in rural areas depending on cases (conditions, application). First, we consider stationary multi-hop wireless networking on static facility based on realistic condition i.e. power transmission monitoring. Surveillance sensor arranged in tandem along a road, river, or power transmission towers network. The monitoring data is sent to as single central management server via one of the gateways at the both edges. Second, we consider large size of message (education/e-learning content) is delivered from the large island to the remote/small island. Due to the geographical location and economical aspect, the availability connection in these remote/small islands only provided by 2G connection with very small bandwidth. Our contribution in chapter 5 and 6 is to employ DTN as an alternative and promising solution to provide low-cost communication in the island scenario.

Chapter 3

Message Transmission Scheduling on Tandem Multi-hop Lossy Wireless Links

In this chapter, we target a tandem multi-hop transmission model on static (stationary) nodes with lossy unreliable wireless links, which can be seen in facility monitoring scenarios where multiple stationary nodes (sensors that can relay messages) are serially arranged along a road, river, or power transmission tower network as shown in Figure 3.1. In this example, a stationary sensor node located at each power transmission tower monitors the facility and periodically generates a monitoring message. Each message is relayed on a lossy unreliable wireless link between two neighbour sensor nodes, which is eventually bound for a single central management server via one of the gateways at the both edges of the network, e.g., electric power substations.

Each node periodically generates a message every T time-slots, and should be relayed to gateways X or Y in a duration of T time-slots in a store-wait-and-forward manner. Link quality (e.g., loss rate) may be bad and independent, because the facility itself not optimized for wireless communications. Random packet losses are uncorrelated in space and time. No interference, two active links are distant, more than two hops in the same direction and one hop in the opposite direction using omni antenna without special cancellation. Our goal is

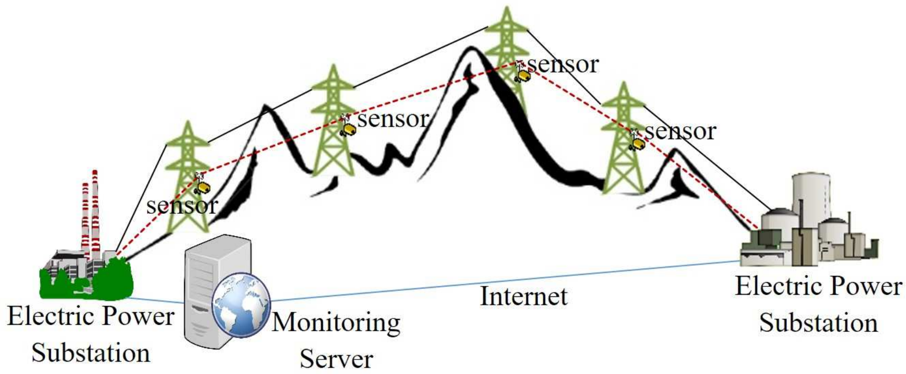


Figure 3.1: Real-world facility monitoring scenario

to maximize the probability that all messages will reach a gateway successfully in which all nodes are equally important and generate messages at the same rate.

We propose a framework for message transmission scheduling on tandem multi-hop lossy wireless links that consists of; (i) a static global time-slot assignment over all links to avoid unnecessary interferences, (ii) a local message selection for transmission including a naive XOR network coding-based redundant transmission for proactive recovery over assigned time-slots on each link to recover lost messages. Item (i) is analytically derived by a central high-performance server based on each individual link's message loss rate (which is assumed to be stable over some time duration), while item (ii) is light-weight and simply done by each node. We do not need to assume any advanced but complicated physical layer and MAC layer functions such as adaptive moderation, interference cancellation, CSMA/CA, high-dimensional network coding, and ACK/NACK-based reactive recovery. On the other hand, to realize item (i), we need to assume a protocol between the server and each node by which the server can estimate the loss rate of each link averaged over some time interval and can inform each node of the global scheduling decision. This mechanism is not treated in this chapter and remains as future work.

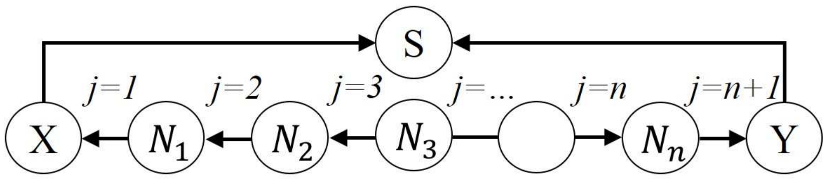


Figure 3.2: Two-gateways single-directed model

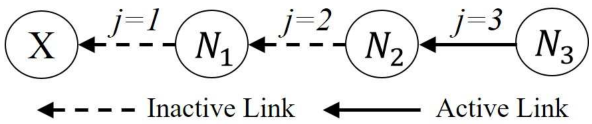


Figure 3.3: Interference avoidance condition

3.1 Tandem Multi-hop Transmission Model

A simplified tandem multi-hop transmission model (Figure 3.2) is used in which n nodes ($j = 1, 2, \ldots, n$) are connected in tandem and each node periodically generates a message at the beginning of every "one circle" (consisting of T time-slots [e.g., sec]). A message generated at source node k is denoted as message k ($k = 1, \ldots, n$). Each message can be transmitted on a link from a node to an adjacent in a single time-slot, should be relayed in a store-wait-and-forward manner from its source node to either of two gateways (X and Y) at the edges of the tandem, and then will be forwarded from the gateway to central server S via a reliable network. Link j connects two nodes j and $j-1$ with loss rate q_j ($0 < q_j < 1$) that is the probability of message loss on link j. We assume that each message should reach either node X or Y within T time-slots (i.e., within the current time circle).

We adopt a single directed model in which, for some separation node m, messages generated at nodes $1, 2, \ldots, m$ will be destined for X and those generated at nodes $m+1, m+2, \ldots, n$ will be destined for Y. We call it m-($n-m$) separation model. Figure 3.2 shows 3-($n-3$) separation model where messages generated at nodes N_1, N_2, and N_3 are sent to gateway X

and other messages are sent to Y. In this single directed model, we can treat each direction (each side of the separation model) independently after deciding a separation model. Therefore, in the proposed scheme, for a given separation model, we analytically derive a good (possible best) performance static global time-slot assignment for each side and compute the total performance by combining both sides, i.e., both directions, of the model. By examining the best performance of each possible separation model in this way and comparing them, we can finally select the best performed one among all possible global time-slot assignments with all possible separation models in response to environmental conditions.

3.2 Proposed Message Transmission Scheduling

The proposed framework consists of:

- a static global time-slot assignment over all links with a choice of separation model, and
- a local message selection for transmission including a naive XOR network coding-based redundant transmission for proactive recovery over assigned time-slots on each link,

which should be appropriately combined in order to statically avoid conflicts among simultaneous transmissions on adjacent links or links within an interference range, and at the same time, to redundantly but efficiently send messages on lossy links. The proposed framework assume centralized system in which server can know the topology and estimate the link loss rates, decides a global static time-slot assignment, and tells the decided time-slot assignment to each node. Each node keeps the synchronized time.

3.2.1 Static Global Time-slot Assignment

A static global time-slot assignment is considered to avoid conflicts among simultaneous transmissions on adjacent links as well as to give more chances to redundant transmission to worse (i.e., more lossy) links. At each time-slot, one or more links are assigned as active, and on each active link, a message can be transmitted in this time-slot. The active links are statically and globally determined, and not changed regardless of each transmission result. We assume that wireless transmission of a message at node j affects two adjacent nodes $j-1$ and $j+1$. For example, in Figure 3.3, N_1 and N_3 should not send messages to the next nodes at the same time-slot to avoid interference at N_2. This simple and homogeneous assumption is for conciseness and can be changed accompanied with a more complicated constraint condition on time-slot assignment.

To derive an "optimal" static time-slot assignment with static message selection for re-transmission of original messages, we adopt the product of the success delivery probabilities for each individual node as the objective function to be maximized. This objective function can be interpreted as the probability that all messages are successfully delivered to the server if the message losses on links are independent. Although there are diverse possible patterns for static global time-slot assignment that can avoid conflicts among simultaneous transmissions on adjacent links, we can consider "the links far from the destination (upper-side links) first" restricted patterns without loss of generality in optimization for the above objective function.

Given (fixed) node k, we focus only on message k (a message generated by node k) that is destined for gateway X. Like Figure 3.4, the message transmission scheduling according to a static time-slot assignment with static message selection for re-transmission of original messages is as follows.

1. First, send the message on the first hop link, i.e., link k, to node $k-1$ during u_k time slots repeatedly.
2. Next, on the second hop link (link $k-1$), send the message to node $k-2$ in u_{k-1} times similarly,
3. Do it in a similar manner to descendant of the link and so forth, and
4. Finally on the last hop link (link 1), send it to X in u_1 times.

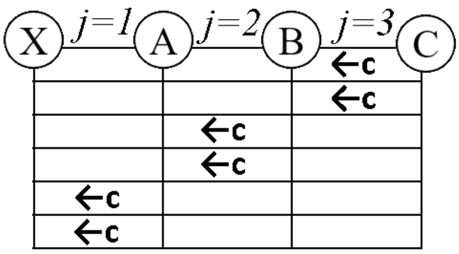


Figure 3.4: An assignment pattern for message C

For conciseness, we explain the optimization in one direction (i.e., on one side of a separation model) with an example in 5-node case shown in Figure 3.5. Note that this optimization example for 5-nodes can be reduced to 4 nodes and be extended to more than 5 nodes accompanied with different condition analysis.

In this case, since the number of nodes in a single direction exceeds three, there are two or more links that can be active at the same time-slot (i.e., they can transmit messages simultaneously) because they are displaced and not interfered. This makes the possible assignment patterns more complicated than a very simple one like Figure 3.4. For example, messages generated at nodes E and B can be transmitted simultaneously at the same time slot. As a result, messages generated at node B may be transmitted on link 2 and link 1 with two separated durations. In such situations, we introduce a term "early-stage transmission", for the transmission in possible time-slots (stage) earlier than the normally assigned time-slots, to be distinguished from "normal-stage transmission". If the number of nodes in one direction increases, there can be more than one early-stages for some links close to the gateway.

The whole static scheduling is represented as follows.

- s_1, s_1': the number of time-slots on link 1 for a message from A (message A in short) for early-stage transmission and for normal-stage transmission, respectively.
- t_1, t_1': the number of time-slots on link 1 for message B, for early-stage transmission and for normal-stage transmission, respectively.

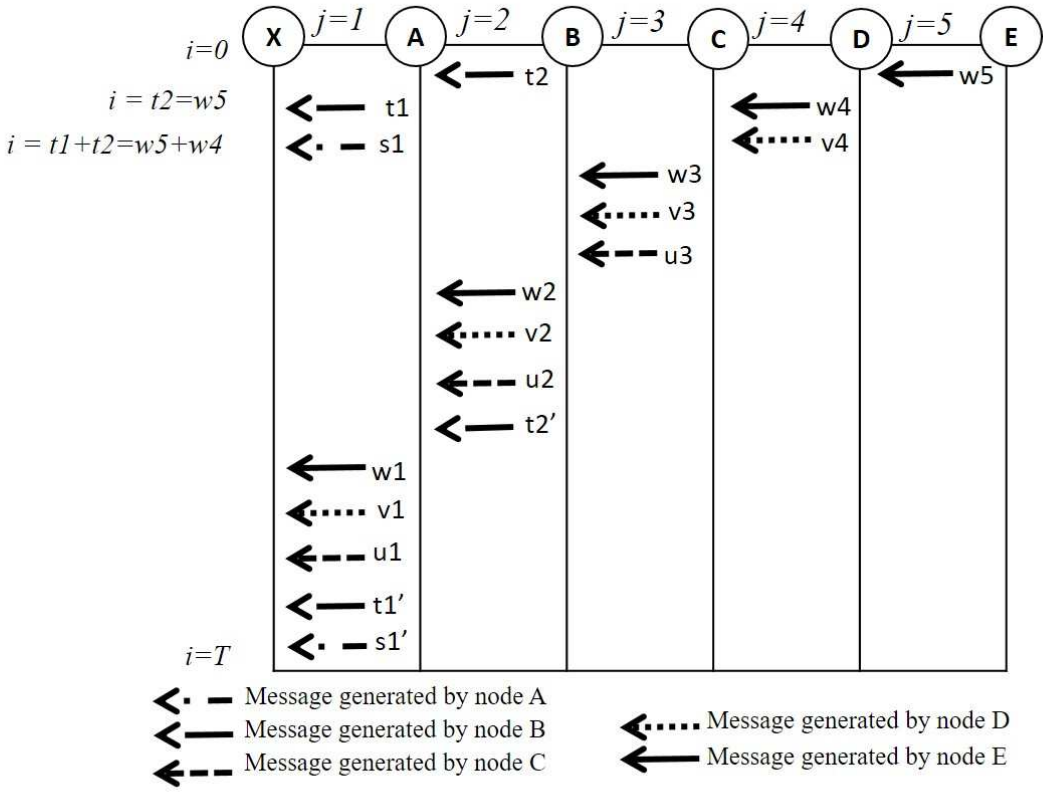


Figure 3.5: Five-nodes case example

- t_2, t'_2: the number of time-slots on link 2 for message B, for early-stage transmission and for normal-stage transmission, respectively.
- u_j ($j = 1, 2, 3$): the number of time-slots on link j for message C.
- v_j ($j = 1, 2, 3, 4$): the number of time-slots on link j for message D.
- w_j ($j = 1, 2, \ldots, 5$): the number of time-slots on link j for message E.

On the above assignment pattern, the success delivery probabilities of each node, $M_1, M_2, \ldots, M_5$ have explicit forms by using $q_1, \ldots, q_5$ ($0 < q_j < 1$) which are message loss rates on links $1, \ldots, 5$, respectively.

The optimization problem to find $\mathbf{x} = (s_1, s'_1, t_1, t'_1, t_2, t'_2, u_1, u_2, u_3, v_1, \ldots, w_5)$ is as follows.

$$
\begin{aligned}
\max_{\mathbf{x}} \quad & \prod_{k=1}^{5} M_k(\mathbf{x}), && (3.1)\\
\text{subject to} \quad & s'_1 + t'_1 + t'_2 + u_1 + u_2 + u_3 + v_1 + v_2 + v_3 + v_4 \\
& w_1 + w_2 + w_3 + w_4 + w_5 = T, && (3.2)\\
& t_2 = w_5, && (3.3)\\
& s_1 + t_1 = w_4 + v_4, && (3.4)
\end{aligned}
$$

where

$$
\begin{aligned}
M_1 &= 1 - q_1^{s_1+s'_1} \\
M_2 &= (1 - q_1^{t_1+t'_1})(1 - q_2^{t_2}) + (1 - q_1^{t'_1})(1 - q_2^{t'_2})(q_2^{t_2}) \\
M_3 &= (1 - q_1^{u_1})(1 - q_2^{u_2})(1 - q_3^{u_3}) \\
M_4 &= (1 - q_1^{v_1})(1 - q_2 v_2)(1 - q_3^{v_3})(1 - q_4^{v_4}) \\
M_5 &= (1 - q_1^{w_1})(1 - q_2^{w_2})(1 - q_3^{w_3})(1 - q_4^{w_4})(1 - q_5^{w_5})
\end{aligned}
$$

This can be numerically solved by a greedy approach in Integer Programming in general. However, as a more efficient way, we first apply Lagrange optimization method to a "relaxed" version allowing real number solutions, and obtain a real number solution of this relaxed problem. Then we search a good integer solution around the above real number solution.

3.2.2 Five Nodes Case Example

Applying Lagrangian method to the optimization problem consisting of Eqs. (3.1) – (3.4), we obtain:

$$\begin{aligned}
u_1 = v_1 = w_1 &= -\frac{\log(1-\alpha\log q_1)}{\log q_1},\\
u_2 = v_2 = w_2 &= -\frac{\log(1-\alpha\log q_2)}{\log q_2},\\
u_3 = v_3 = w_3 &= -\frac{\log(1-\alpha\log q_3)}{\log q_3},\\
v_4 = w_4 &= -\frac{\log(1-\alpha\log q_4)}{\log q_4},\\
t_2 = w_5 &= -\frac{\log(1-\alpha\log q_5)}{\log q_5}
\end{aligned} \tag{3.5}$$

In addition, we can assume the solution satisfies:

- $s'_1 + t'_1$ is minimized as long as $s_1 + s'_1 \geq w_1$,
- if $t_2 = w_5 \geq w_2$ then an additional t'_2 is not necessary any more.

The derivation procedure to get an optimal solution changes according to the relationship among q_1, q_2, q_4, q_5. More precisely, there are four conditions to be considered – (i) $q_2 \leq q_5$ and $q_1 > q_4$, (ii) $q_2 \leq q_5$ and $q_1 \leq q_4$, (iii) $q_2 > q_5$ and $q_1 > 2q_4$, (iv) $q_2 > q_5$ and $q_1 \leq 2q_4$.

In condition (ii),

- $q_2 \leq q_5$ implies $w_2 \leq w_5$ and $t'_2 = 0$.
- $q_1 \leq q_4$ implies $w_1 \leq w_4$, suggesting $t_1 = w_1,\ s_1 = 2w_4 - w_1$ and $t'_1 = s'_1 = 0$.

Therefore α in Eq. (3.5) can be numerically determined by solving an irrational equation derived from Eq. (3.2) by substituting Eq. (3.5) and the above auxiliary relations.

In conditions (i) and (iii), a similar derivation can be applied. However, in condition (iv), the condition analysis becomes more complicated and there is no single irrational equation to decide a best solution. Instead, each of possible sub-conditions should be examined by solving a corresponding equation, and finally a best solution is decided by comparison. Note

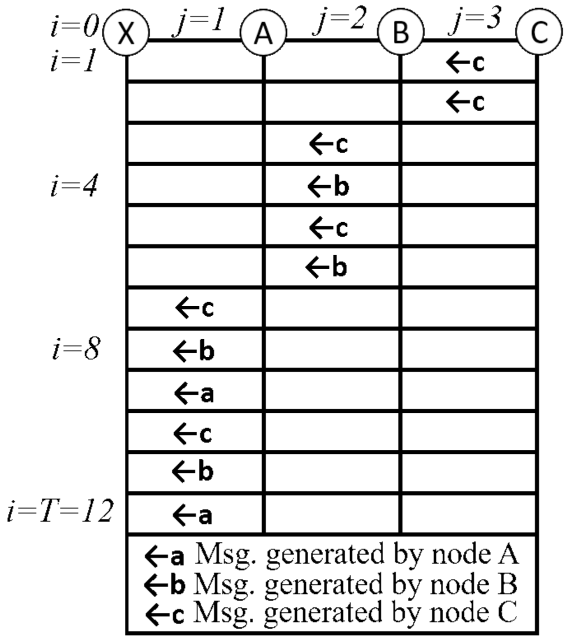


Figure 3.6: Without network coding

that, to apply the derivation to the right-hand side of a separation model, the node indexes are swapped accordingly. When considering the right-hand side of 3-5 separation model in Table 3.1, (q_9, q_8, q_7, q_6) will be renamed as (q_1, q_2, q_3, q_4).

3.2.3 XOR Network Coding-based Message Selection

Network coding is an approach that allows each network (relay) node to generate a new message by combining more than one relayed messages. In a proactive recovery scheme for lost messages, network coding can be used as dynamic and inter-flow forward erasure correction (FEC) in multi-hop wireless transmission. After deciding a static time-slot assignment by the procedure in Subsection 3.3.1, we adopt a fair message selection with naive XOR network coding-based message transmission, in which each node can send an encoded message that is an XOR-combination of available original messages at the node.

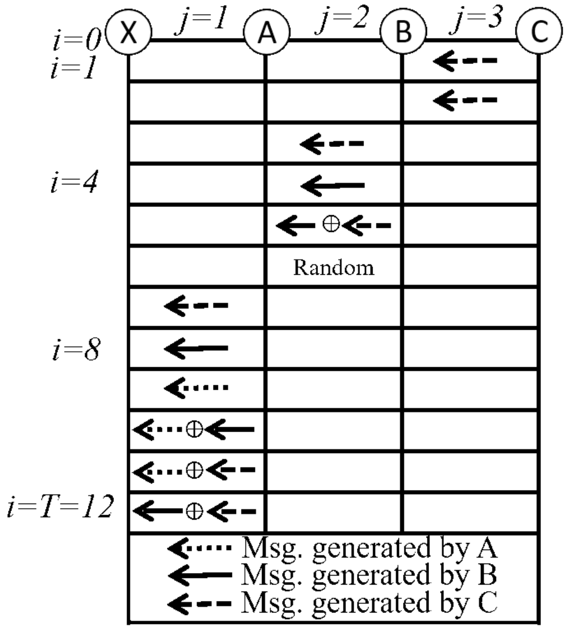


Figure 3.7: With network coding

At each time-slot assigned to the link, one of original or encoded messages is selected to be sent on the link. To make sure that each message has the same chance to be selected, the transmission counter for each message records how many times the message is selected. Original messages, or messages with the lowest value of transmission counter have high priority to select first, then encoded messages will be selected randomly according to the transmission counter value. When all messages have the same transmission counter value, one message will be randomly selected. Figures 3.6 and 3.7 show message transmission scheduling examples without and with network coding implementation.

3.3 Evaluation and Discussion

For model-based numerical simulation and evaluation, the proposed framework is implemented by Java, and a 8-nodes tandem multi-hop lossy wireless network is examined with

Table 3.1: Link Loss Rate Setting Examples

Case	q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8	q_9
1	0.1	0.2	0.3	0.2	0.3	0.3	0.2	0.1	0.2
2	0.6	0.1	0.1	0.3	0.3	0.2	0.3	0.2	0.1

two different link loss rate settings (Cases 1 and 2) in Table 3.1. The total number (T) of time-slots for one time circle is set to 30, 45 and 60.

3.3.1 Static Slot Assignment with Separation Model

As explained in Sect. 3.2, we can find a "good (possibly best)" static global time-slot assignment with a "good (possibly best)" separation model by applying the proposed optimization in one direction explained in Sect. 3.1 for each setting (i.e., Cases 1 and 2 in Table 3.1 using $T = 30, 45, 60$). Figures 3.8 and 3.9 show the obtained good static time-slot assignments for 3-5 model in Case 2, and for 4-4 model in Case 1, respectively, in case of $T = 30$. The probability that all messages are successfully delivered is computed with a static transmission schedule by combining both direction. For the separation point, we have compared all possible model to find the best global static time-slot assignment. In the following simulation evaluation (i.e. Subsections 3.3.2 and 3.3.3), we use Case 2 which is an example of sever situations with imbalanced link loss rates. In Case 2, the best separation is 3-5 model shown in Figure 3.8.

3.3.2 Performance of Static Slot Assignment with Simple XOR Network Coding-based Message Selection

We introduce a comparative static time-slot assignment method in which the number assigned slots for each link is proportional to both the number of message paths passing the link and the loss rate of the link. We call it Loss Rate Aware (LRA).

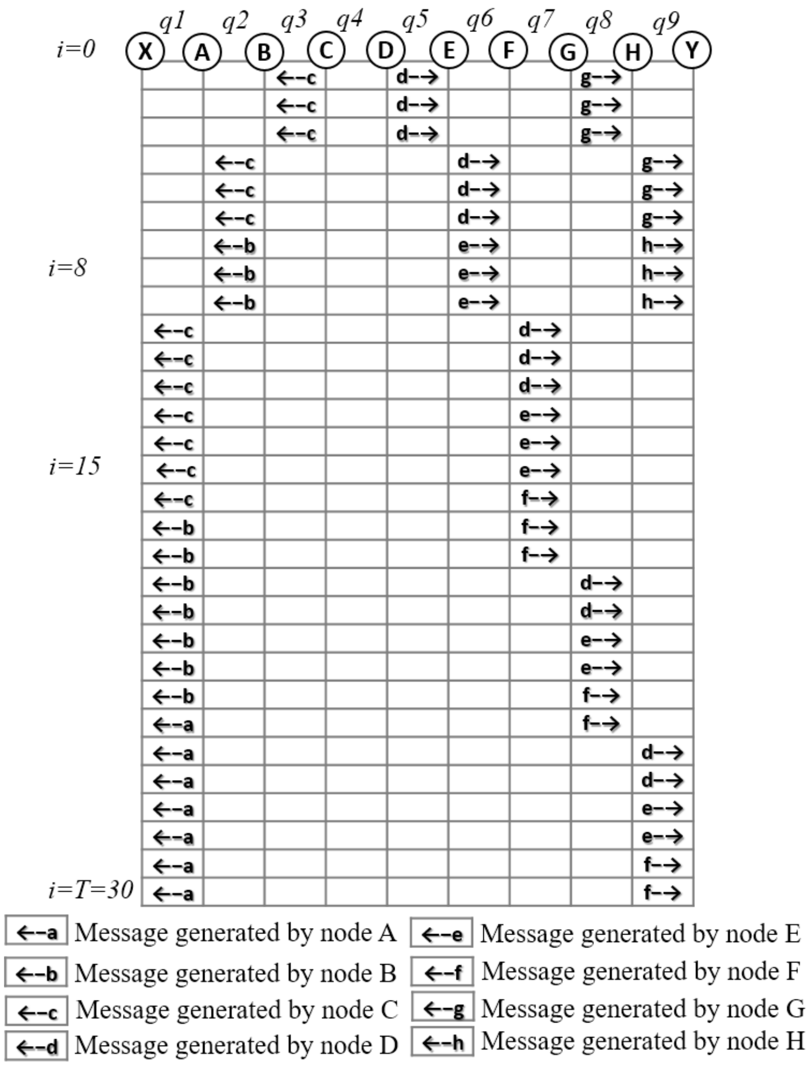


Figure 3.8: Slot assignment and separation model 3-5 model in case 2

Figure 3.10 shows the performance comparison of static time-slot assignment method with static message selection using $T = 30, 45, 60$ in term of success delivery probability of all message. Our proposed method always outperforms the LRA method. Next, we employ simple XOR network coding-based message selection scheme (NC) to all of static slot assignment methods (proposed, and LRA). In general implementation of NC improves the

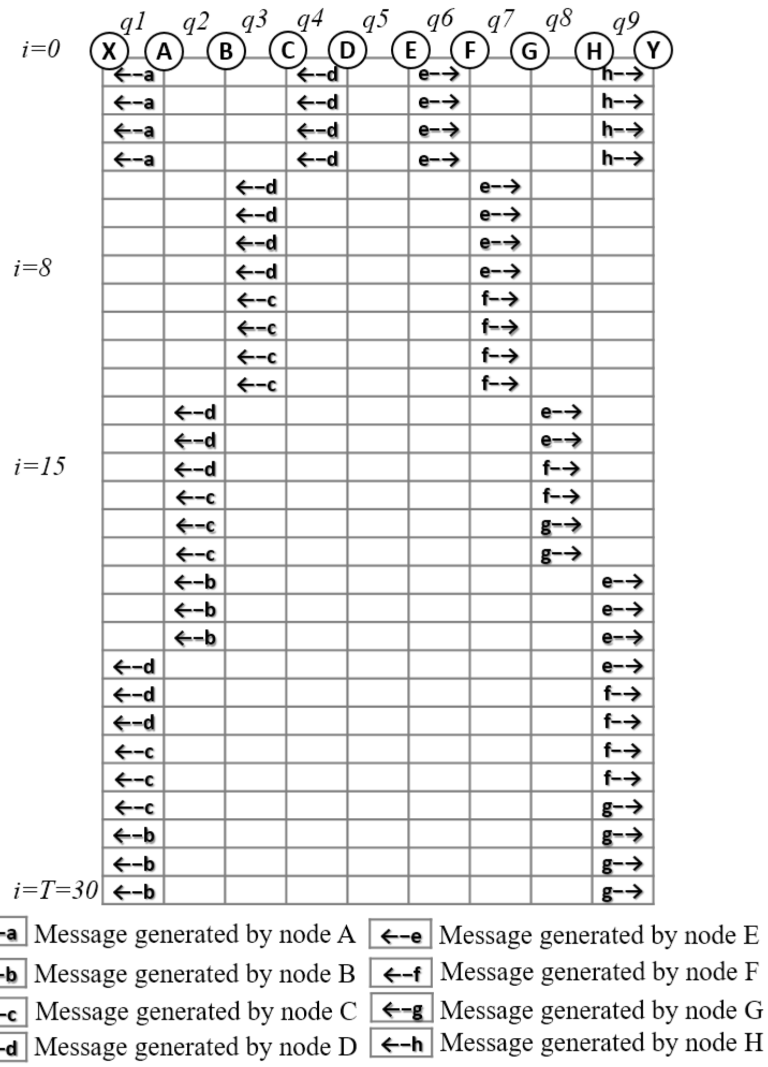


Figure 3.9: Slot assignment and separation model 4-4 model in case 1

performance all of static time-slot assignment methods.

Figure 3.11 shows success delivery probability of each message using $T = 30$. In general, the message generated at the upper-side nodes (the nodes far from its gateway) suffer from a more opportunities of message loss in traveling multiple lossy links. On the other hand, the balance among messages (i.e., source nodes) varies depending on the time-slot assignment.

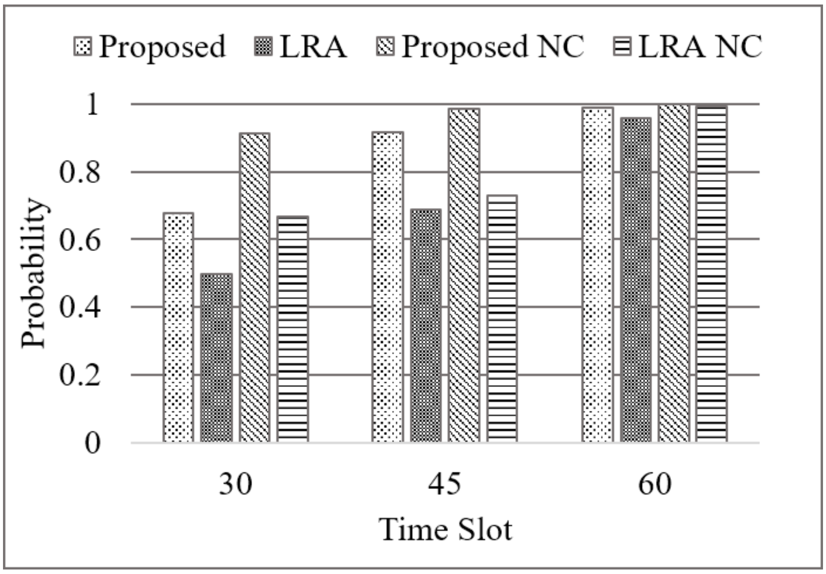


Figure 3.10: Success delivery probability All messages in different static time-slot assignments

In LRA NC method which also gives importance on link loss rate, message *A* and *B* have higher success delivery probabilities. In Proposed NC method, a most fair balance among messages is exhibited.

3.3.3 Performance Comparison with ACK-based methods

As comparative approach, Acknowledgement (ACK)-based reactive recovery is considered. We introduce two ACK-based message transmission methods; Limited-ACK (L-ACK) and Unlimited-ACK (U-ACK). In L-ACK, the sender-side node will attempt to transmit a message on a given link until either an ACK for the message is returned or the number of transmissions reach the total number of time-slots consecutively assigned to the link by the static assignment. When two different messages should be sent on a link within an assigned number of consecutive time-slots, if transmissions of the first message exhaust the assigned time-slots, then the second message cannot be sent at all. In contrast, U-ACK is independent of a

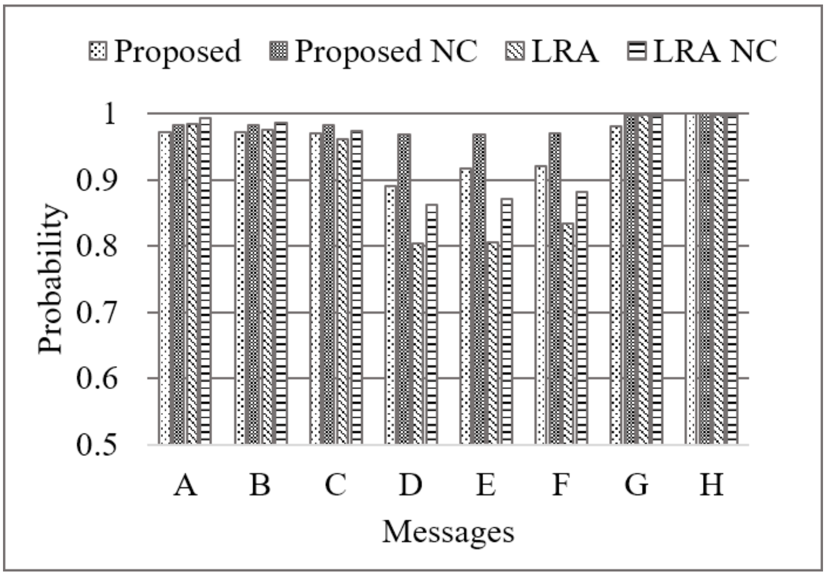


Figure 3.11: Success delivery probability Each message in different static time-slot assignments with $T = 30$

given static time-slot assignment. In U-ACK, the sender-side node will attempt to transmit a message on a given link until ACK for the message is returned, and repeat this process until ACKs for all messages are returned. This process will be repeated from the source node to each downstream node, i.e., upper-side links first until all T time-slots in one time-circle are exhausted. There is no limitation on the number of re-transmissions both for each message and for each link.

In addition, to reflect realistic conditions, we implement a reverse direction loss and delay of ACK by artificially increasing the loss rate value for each link by multiplying 1.2 and 1.4 for U-ACK and decreasing the total number (T) of time-slots by multiplying 0.8 for U-ACK and L-ACK, respectively. We also consider "ideal" ACK with no overhead and no loss to investigate the upper bound performance. In ideal ACK, when a message is successfully received by the receiver-side node, the sender-side node immediately knows that without any time delay and error.

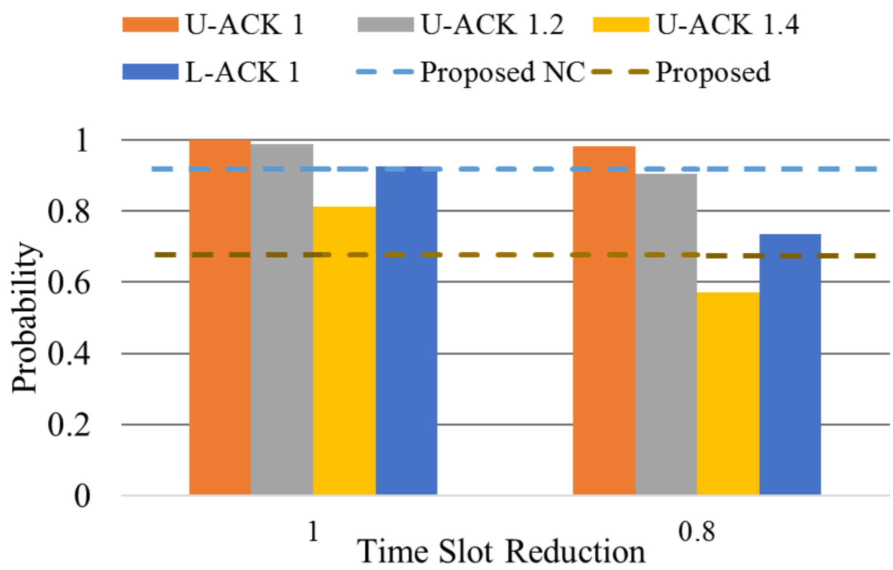


Figure 3.12: Success delivery probability of all messages for ACK-based methods and proposed NC method with $T = 30$

Figure 3.12 compares the success delivery probability of all messages by the proposed NC method and ACK-based methods. The ideal condition (with no loss and delay of ACK) are identified as time-slot reduction of 1 by indicating the x-axis and the legend names of U-ACK 1 and L-ACK 1. The realistic conditions (with reverse loss and delay) is identified as time-slot reduction of 0.8 (that is $T = 24$ instead of 30) and legend names U-ACK 1.2 and U-ACK 1.4. When there is no time slot reduction, U-ACK 1 outperforms Proposed NC and L-ACK 1, in consistent with our expectation that the "ideal" U-ACK 1 will show the upper-bound performance in terms of the success delivery probability of all messages.

On the other hand, Proposed NC achieves the same performance of L-ACK 1 with no loss and no delay. Then, in realistic conditions (i.e., the number of time slots is reduced from 30 to 24, and the link loss rates are increased) for ACK-based methods, Proposed NC achieves the same performance of U-ACK 1.2. These results suggest that Proposed NC is

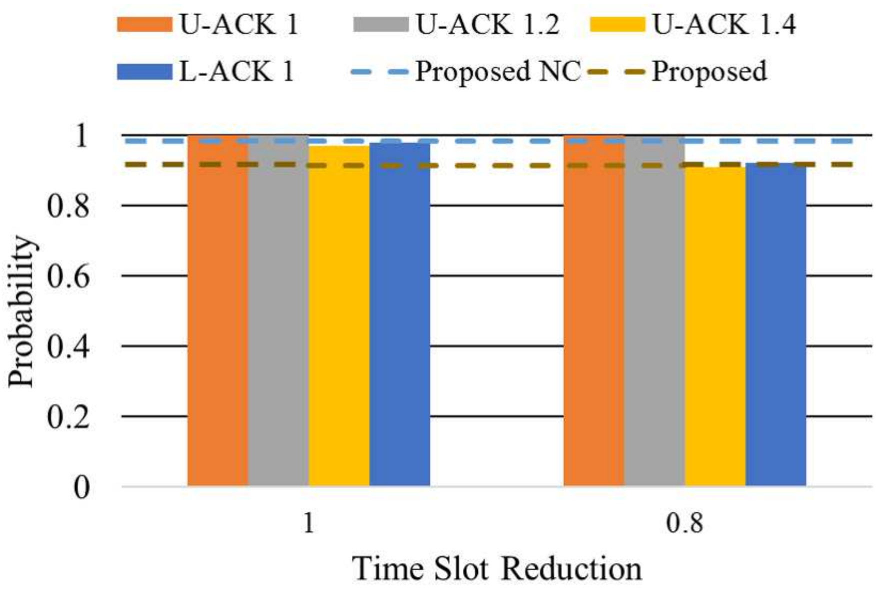


Figure 3.13: Success delivery probability of all messages for ACK-based methods and proposed NC method with $T = 45$

comparable to or better than ACK-based methods in realistic conditions. In ideal condition, ACK-based reactive recovery of lost packets is resource efficient in theory compared to proactive recovery. However, implementation of ACK-based retransmission model will increase the cost and complexity of each node of a real system. In contrast, our scheme can assume very low-cost nodes while assuming a centralized management.

Figure 3.13 shows the success delivery probability of all messages with increasing of time slot from 30 to 45. In general increasing the number of time slots will increased the performance of all methods. When there is no time slot reduction, U-ACK always show the upper bound performance. Our Proposed time slot assignment with NC achieved almost the same performance with U-ACK although in condition with reverse loss and delay.

3.4 Conclusion and Future Work

In this research, we have proposed a framework for message transmission scheduling on tandem multi-hop transmission model with lossy wireless links. By applying mathematical optimization, we can obtain a static assignment solution for the number of time-slots that assigned to each link. We also have introduced a simple XOR network coding-based scheme for proactive message transmission on proposed static time-slot assignment. Simulation results showed the probability that all messages are successfully delivered to the server (via gateways) by our proposed framework is comparable to and sometimes even better than that by ACK-based reactive recovery schemes which are more complex and costly. This suggests the effectiveness of our approach that combines a static global time-slot assignment (to avoid unnecessary interferences) and a local message selection for transmission with a simple network coding-based proactive message re-transmission (to recover lost messages). For large adaptability, we need to extend the model that can treat different scenarios such as heterogeneous message generation rates and more than two gateways (e.g., on a tree topology).

Chapter 4

Comparison of DTN Routing Protocols in Realistic Scenarios

In this chapter, using the opportunistic network environment (ONE) simulator [28], we analyze the performance of different SCF routing protocols in DTN to reveal their advantages and disadvantages in scenarios close to real-world practical situations using cars, buses, and a ferryboat on two islands. We investigate four routing protocols Epidemic (EP) [7], MaxProp (MP) [14], PRoPHETv2 (PV2) [13], and Direct Oracle (DO our proposed routing in [5]) by varying the number of created messages, the message size, the transmission range, and the transmission speed using three performance metrics; total size of delivery messages, delivery probability, and overhead ratio.

4.1 Routing Protocols in DTNs

Message forwarding through DTN is a challenging problem. In recent developments, a lot of algorithms have been incorporated to provide maximum throughput and improve delivery ratio. Almost all forwarding and routing schemes use an asynchronous message passing (also referred to as store-carry-forward) scheme. Of the four protocols, MP, PV2, and DO use contact history for decision-making in their forwarding methods while EP does not. In the four protocols, each message has a time-to-life (TTL), which limits for how long a copy of the message can be in the network before reaching its destination.

4.1.1 Epidemic (EP)

EP is a protocol that is basically a flooding mechanism, in that each message spreads like a disease in a population without priority and without limit. When two nodes encounter each other they exchange a list of message IDs and compare those IDs to decide which message is not already in storage in the other node. The next phase is a check of available buffer storage space, with the message being forwarded if the other node has space in its buffer storage.

4.1.2 MaxProp (MP)

MP also is a flooding mechanism, but the messages are explicitly deleted once a copy is delivered to the destination, which is notified by distributing an acknowledgment message. In addition, MP forwards messages to other nodes in specific order that takes into account message hop count and message delivery probability based on its history, that is a combination of destination dependent (the cost to reach the destination) and destination independent (the current number of hops that a message has traversed) ones. MP has three mechanisms in buffer management to realize a tactic of aggressive replication (copies) and aggressive deletion of messages.

4.1.3 ProPHETV2 (PV2)

PV2 updates the functionality that was used in PRoPHET [9]. It uses delivery predictability as a metric to evaluate the likelihood of one node being able to deliver a message to the destination. Forwarding is based on delivery predictability and is history based, and it attempts to estimate which node has the highest likelihood of being able to deliver a message to the final destination based on node-encounter history.

4.1.4 Direct Oracle (DO)

DO is a routing protocol we developed in previous research. It adopts a history-based forwarding in which a message is only forwarded to a node that has the destination address in its contact list, with each node updating its contact list when it encounters other nodes. The destination address can be distinguished from other addresses; the destination address is included in source node contact list initially, and will be added to contact list of a node when the node encounters other node whose contact list includes the destination address or encounters the destination node itself.

4.2 Comparison of Routing Protocol Techniques

Table 4.1 shows a comparison of SCF routing protocols in DTNs based on a study of literature [18].

4.2.1 Buffer Management

Here we look at the method of ordering messages based on a node's knowledge. When a new message arrives in the buffer and there is no room for it, a deletion policy selects messages to be discarded according to their ordering. Due the limited buffer storage of DTN and the fact that in sparse networks a message can be queued for a long time, an efficient buffer management policy must be adopted to avoid the deletion of important messages. It consist of message scheduling and drop policy, random is the default message scheduling, and drop oldest is default drop policy, while in another method the policy depends on routing algorithms. In addition, it is common of all routing protocols when there are new incoming message and buffer storage is not enough, the oldest messages (by receiving time) in message

Table 4.1: My caption

Routing Protocols	**Techniques**			
	Buffer Management		**Forwarding/ Message Selection**	**Copy Policy**
	Msg. Scheduling	**Drop Policy**		
Direct Oracle	Random	Drop Oldest	History Based	Unlimited
Epidemic	Random	Drop Oldest	Always	Unlimited
MaxProp	Hop Count Based	ACK. based and Drop Oldest	History Based	Unlimited
ProPHETV2	Random	Drop Oldest	History Based	Unlimited

queue will be dropped first (drop oldest). The message is also drop when message live-time (TTL) is less than zero.

4.2.2 Forwarding

Forwarding is a method for sending a message from the messages queue. In some cases, a message is selected on the basis of the same ordering method as defined by queue management. When two nodes encounter each other, it will be determined whether the message will be forwarding or not.

- Direct Delivery. Messages are delivered only to the final destination.
- Always. When encountered, a message spreads like a disease throughout a population.
- Knowledge based. Messages are forwarded based on current knowledge in terms of contextual, historical or social information.

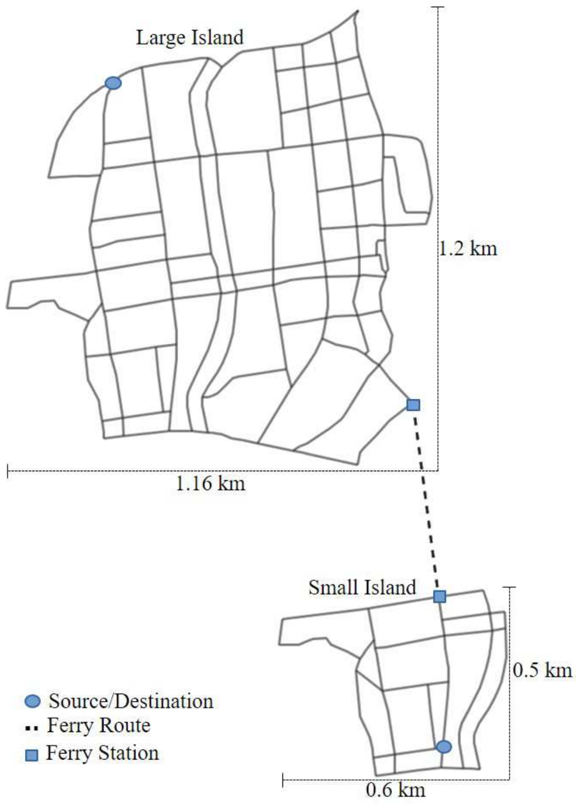


Figure 4.1: Simulation Area

4.2.3 Replication

Replication controls and defines the number of copies of a message in a network.

- Single copy. Only one copy of a message exists in network storage at any given time.
- Limited. The number of copies of a transmitted message are limited.
- Controlled. The number of copies is controlled according to prevailing conditions.
- Unlimited. There is no obstacle to the number of copies of a message in a network.

4.3 Simulation Setup and Performance metrics

Routing protocol performances were analyzed by means of simulation run on the ONE simulator, we considered scenarios based on real-life assumptions as shown in Figure 4.1. In our scenarios, two islands (Island A: main, Island B: small) are connected by a ferryboat, with buses and cars as vehicle nodes on each of the islands, and four static nodes as source, destination, and stations, with Wi-Fi as a network interface with two combinations of transmission speed and transmission range (1 Mbps 25 m and 5 Mbps 5 m). Table 4.2 summarizes the simulation parameters of the evaluations.

For the buffer-management issue, we used two message sizes, and three numbers of created messages. The best case is the lowest number of created messages of a small size (i.e. 256 messages, 0.1 MB) and the worst case is the largest number of created messages of a large size (1,536 messages, 2 MB). The messages are generated only in one source node and delivered to one destination node, new messages generated within four hours according to the maximum number of created messages. A message will be expired according to time-to-live (TTL) value, in this case we used TTL = 120 minutes. For the routing protocols parameter, we used the default parameters of the ONE simulator. EP, DO and MP do not have an initial parameter, while PV2 have an initial parameter for delivery predictability, Table 4.3 summarizes the routing parameters of PV2.

We use the following three metrics to measure the performance of the different routing protocols:

- Delivery probability. M is the number of messages sent to the destination node, and D is the number of messages actually delivered to the destination.

$$DeliveryProbability = \frac{D}{M} \tag{4.1}$$

- Overhead ratio. This shows how many redundant packets are relayed in the delivery of one message, which simply reflects transmission efficiency. R is the number of

Table 4.2: Simulation Parameter

Parameter	**Value**
Simulation Time	8 Hours
World Size	1,200m x 2,200m
Movement Model	Car Movement, Bus Movement, Stationary Movement
Node Buffer Size	Car, bus, source, destination = 200MB
	Station A and B, Ferryboat = 2,100MB
Interface Type	Wi-Fi
Interface Transmit Speed	5 Mbps, 1 Mbps
Interface Transmit range	5 m, 25 m
msgTTL	120 Minutes
Node Movement type	Car Movement, Bus Movement, Stationary Movement
Node Speed	Bus = 5-20 km/h, Car = 10-30km/h, Ferry = 2km/h
Total Message Created	256, 768, 1,536 messages
Message Created duration	From 0s to 14,400s (4 hours)
Message Size	0.1 MB and 2MB
Node Numbers	Island A Car = 6, Bus = 4, Station = 2,
	Island B Car = 4, Bus = 3, Station = 2,
Warm up time	1,800 seconds

Table 4.3: ProPHET V2 Initial Parameter

Parameter	**Value**
Delivery predictability initialization	0.5
Typical interconnection time in seconds	1,800
Delivery predictability transitivity scaling constant default	0.9

forwardings of a copy of a message between nodes.

$$OverheadRatio = \frac{R - D}{D} \tag{4.2}$$

- Total size of delivered messages is the total volume of messages successfully delivered to the destination. Z is the size of a message.

$$TotalSizeofDeliveredMessages = D \times Z \tag{4.3}$$

4.4 Simulation Results

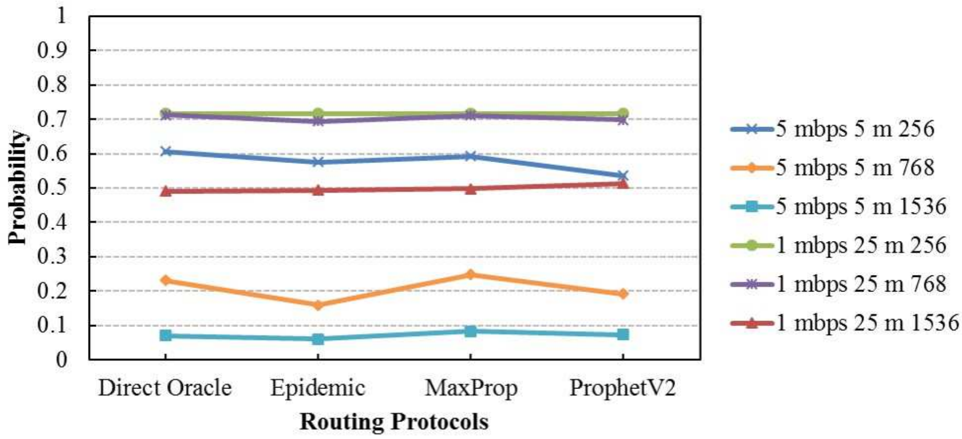
4.4.1 Delivery Probability

Figure 4.2(a) shows that the delivery probability for small messages decreases in all routing protocols as the number of created messages (message generating rate) increases. For the 5 Mbps 5 m case, EP and PV2 are inferior to DO and MP in 768 messages; while for the 1 Mbps 25 m case, PV2 is inferior to the other protocols in 256 messages.

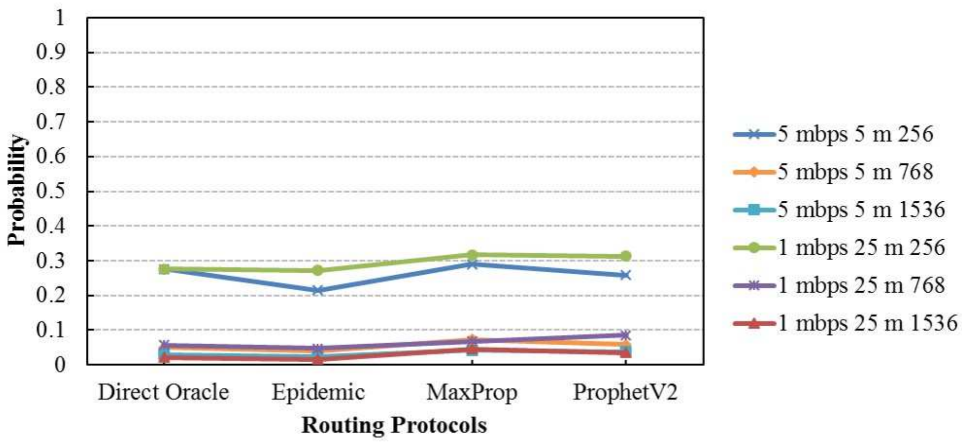
For large messages (Figure 4.2(b)), the performance differences among routing protocols become significant. In almost all cases EP is inferior to the other protocols, DO does not have such a good delivery probability as MP and PV2; under one condition PV2 has a higher delivery probability, but under other conditions it has a lower delivery probability than MP and DO. As shown in Table 4.4, for large messages, the performance is affected by the buffer-management issue (i.e. buffer storage becomes full quickly), note that the car and bus nodes have 200 MB buffers, while the other ferryboat and station nodes have 2,100 MB buffers.

4.4.2 Overhead Ratio

As shown in Figure 4.3(a), for small messages the overhead ratio for all routing protocols is almost same except for 5 Mbps 5 m 768 and 1,536 messages. In this case, EP, as a simple



(a) 0.1 MB of file size



(b) 2 MB of file size

Figure 4.2: Delivery probability

routing protocol, has a higher overhead ratio, which simply tries to send all messages stored to all possible connections even when the message-generating rate is high. This condition also occurred in PV2 in 768 messages and DO in 1,536 messages, but was not as significant as in EP. Figure 4.3(b) exhibits more diversity in the overhead ratio. EP has a higher overhead than the other routing protocols except in 1 Mbps 25 m, 256 messages. DO has a higher overhead than MP and PV2 in some cases. MP exhibits generally good performance.

Table 4.4: Number of buffer full condition for 1 Mbps 25 m

Created Messages	Large Messages				Small Messages			
	DO	**EP**	**MP**	**PV2**	**DO**	**EP**	**MP**	**PV2**
256	12	15	4	15	0	0	0	0
768	42	47	66	58	0	0	0	0
1536	54	61	60	65	0	0	0	0

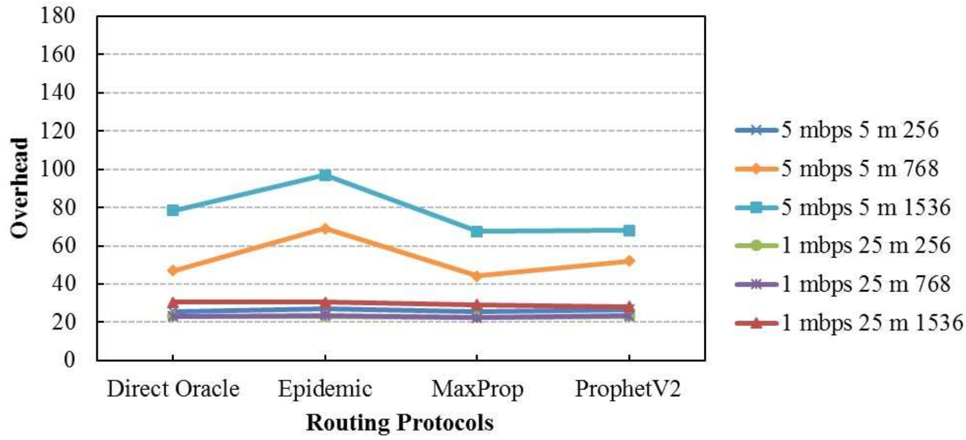
4.4.3 Total size of delivered messages

Figure 4.4(a) shown the total size of delivered messages for small messages. In a 1 Mbps 25 m case, it increases as the number of created messages increases, but this did not happen in the 5 Mbps 5 m case. All protocols show a similar performance except for the slight inferiority of EP and PV2 in 5 Mbps 5 m, 768 messages, and the slight superiority of PV2 in 1 Mbps 25 m, 1,536 messages. Although all cases have the same possible bandwidth-time quantity for forwarded messages (5 Mbps 5m and 1 Mbps 25 m), a long transmission range improves significantly the total volume of delivered messages.

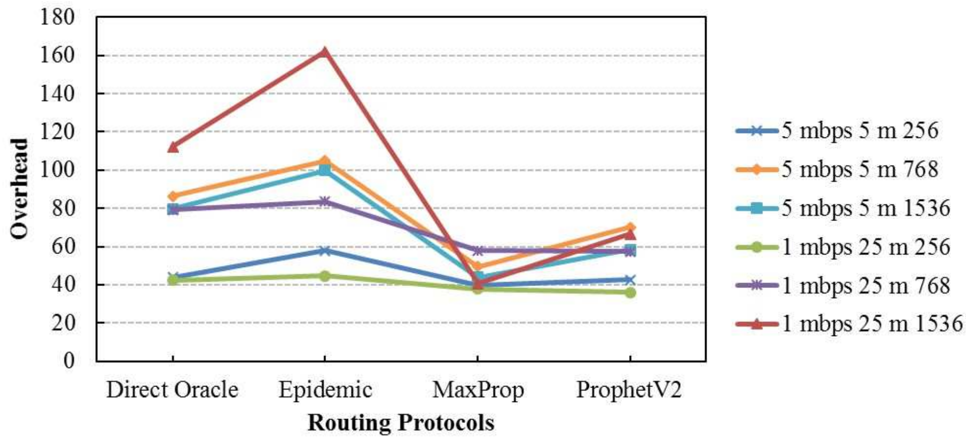
Figure 4.4(b) shows the performance for large messages, as can be seen, the different protocols exhibit significant differences. In some cases, MP and PV2 outperform DO and EP; with EP exhibiting a markedly worse performance than the other routing protocols. For small messages, the total size of delivered messages is maximized when the number of messages is the largest (1,536) in a 1 Mbps 25m case. Contrarily, for large messages, the total size is maximized when the number of messages is the smallest (256).

4.4.4 Difference transmitt range and transmitt speed impact

In this subsection, we investigate the impacts of the interface transmit range and the interface transmit speed combination (1 Mbps 25 m and 5 Mbps 5 m). In the previous subsection, we ascertained that a long transmission range offers better performance than a short transmission



(a) 0.1 MB of file size

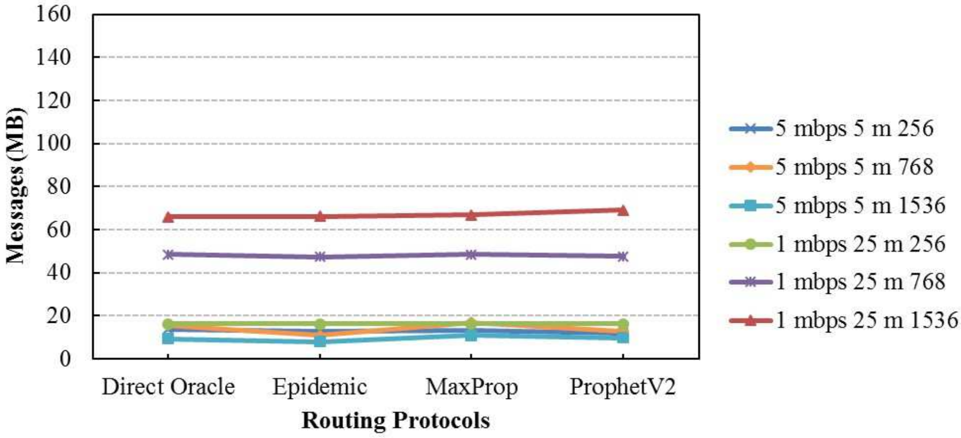


(b) 2 MB of file size

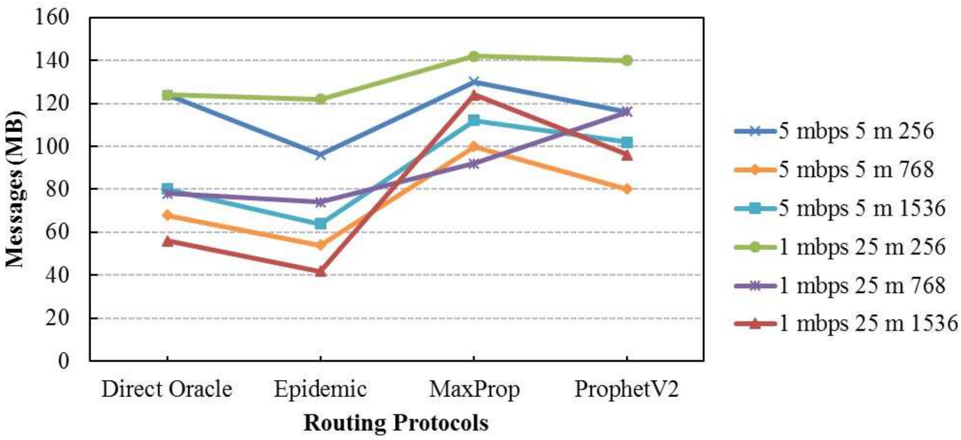
Figure 4.3: Overhead ratio

range.

As shown in Figure 4.5, if node A and node B have the same speed in the intersection route, in a 1 Mbps 25 m case, node A can make contact with node B. On the contrary, in a 5 Mbps 5 m case, node A cannot reach node B. This affects the total contact time in a 1 Mbps 25 m case that is longer than in a 5 Mbps 5 m case (Figure 4.6). We also found that in a 5 Mbps 5 m case the total contact time is not enough to distribute 1,536 messages as shown



(a) 0.1 MB of file size



(b) 2 MB of file size

Figure 4.4: The total size of delivered messages

in Table 4.5. In a 1 Mbps 25 m case, the total number of relayed messages increased in line with the increase in the number of created messages, increasing from about 11,000 messages in a 768 created-messages case to about 22,000 messages in a 1,536 created-messages case. However, in a 5 Mbps 5 m case, it was only about 7,000 messages while the number of created messages increased from 768 messages to 1,536 messages.

In large messages, we found that the number of relayed messages in a 1 Mbps 25 m case

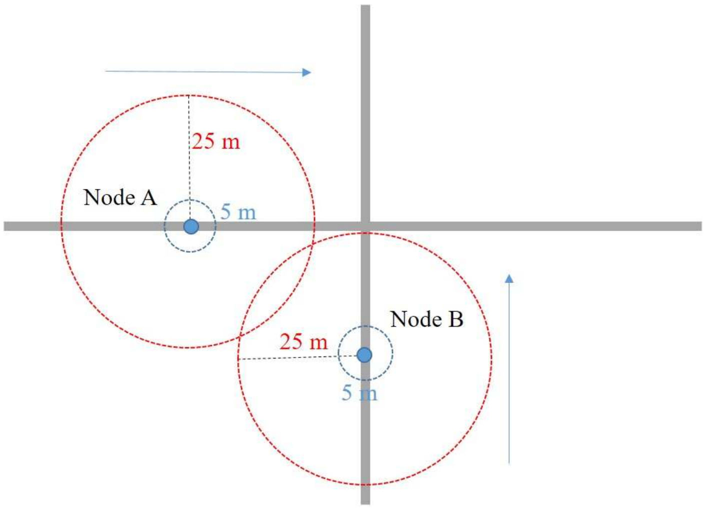


Figure 4.5: Difference in short-range and long-range transmissions

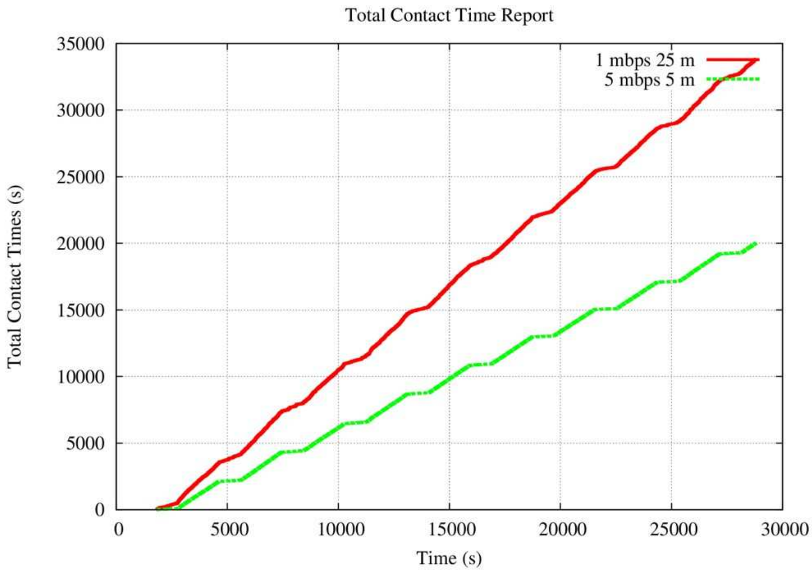


Figure 4.6: Total contact time report of 1 Mbps 25 m and 5 Mbps 5 m case

and a 5 Mbps 5 m case are almost the same (about 3,000 messages) although the total contact time in the 1 Mbps 25 m case that is longer than 5 Mbps 5 m case. In some cases, the relayed

Table 4.5: Total Number of relayed messages for small message case (0.1 MB)

Transmit Speed and Range	**Created Messages**	**Relayed Messages**			
		DO	**EP**	**MP**	**PV2**
1 Mbps 25 m	768	11,728	11,648	11,281	11,550
	1,536	20,802	20,929	20352	20,285
5 Mbps 5 m	768	7,539	7,563	7638	6,892
	1,536	7,626	8,117	7,681	6,840

messages in a 5 Mbps 5 m case are higher than in a 1 Mbps 25 m case. The assumptions considered for this condition is that the buffer storage cannot accommodate all of the relayed messages, and because buffer storage will likely become full more quickly than in a small message case, new messages could not be forwarded to another node until the old messages were dropped from buffer storage.

4.4.5 Ferryboat route impact

We assumed that two islands were connected by a ferryboat via two stations employed as gateways on both islands. On Island A, cars and buses forward messages to the ferryboat via Station A, while on Island B, cars and buses receive messages from the ferryboat via Station B. The travel time of the ferryboat from Station B to Station A is about 15 minutes, and the waiting time at Station A before returning to Station B is about 30 minutes, thus the total travel time of a ferryboat trip from Station B to Station A and back to Station B is about 90 minutes (Figure 4.7).

For this analyze, we used a 1 Mbps 25 m case with large messages and 1536 generated messages. The ferryboat timings (waiting time and trip time) affected the number of messages delivered to the destination node, Table 4.5 shows the number of delivered messages at Station A, Station B, Ferryboat, and Destination.

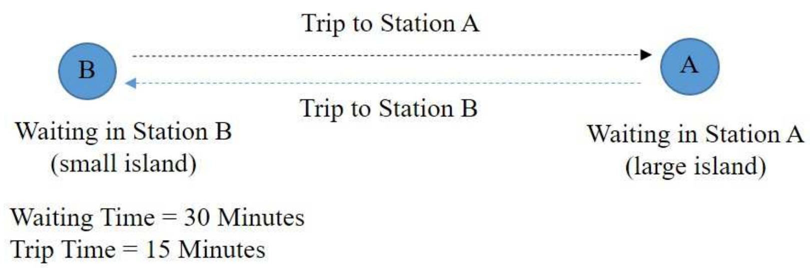


Figure 4.7: Ferryboat travel time from Island B to Island A and back to Island B

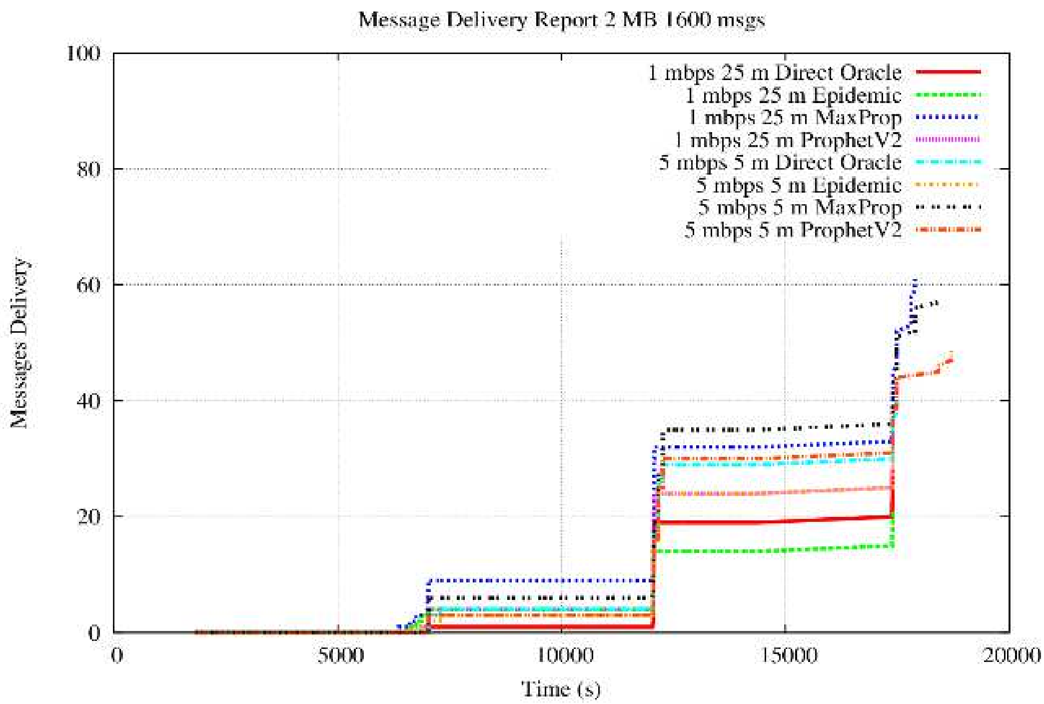


Figure 4.8: Message delivery report for 2 MB, 1536 messages, 1 mbps 25 m case all of routing protocols

As shown in Table 4.6, almost all routing protocols have similar results based on the travel time of the ferryboat. The number of delivered messages to Station B is about half the number of delivered messages to the ferryboat. This occurred because some messages

Table 4.6: Number of messages deliever to stations, ferryboat, and destination node for 1Mbps 25m, 2MB, 1,536 messages

Delivered Messages	**Routing Protocols**			
	DirectOracle	**Epidemic**	**MaxProp**	**Prophet**
Station A	148	153	154	164
Ferryboat	113	112	119	132
Station B	68	53	69	63
Destination	67	51	61	59

had been dropped from the storage buffer before the ferryboat arrived at Station B, due to the TTL having expired. Figure 4.8 shows that the lag time that occurred in delivered messages depends on the ferryboat travel time, there are three duration times for each number of messages delivered to the destination node (6,000 s, 12,000 s, and 17,000 s). The message-delivery reports of all routing protocols varies since 6,000 s, but consistently delivered a number of messages in the three duration times.

4.5 Conclusion and Future Work

In this chapter we analyzed the performance of SCF-based DTN routing in scenarios where a number of messages generated by a single source node on the main island are to be delivered to a single destination on the small island, with a lifetime (TTL) of 2 hours. The two islands are connected only by ferryboat transportation. This can be seen as a real-world practical situation arising in developing regions. Four SCF routing protocols Epidemic (EP), MaxProp (MP), PRoPHETv2 (PV2), and Direct Oracle (DO our proposed routing) were examined by varying the number of created messages (message generating rate), the message size, the transmission range, and the transmission speed. While our investigation is in the preliminary stage, our observations revealed complex dependencies of performance on both scenario parameters and routing protocols, and implies there is no single best routing protocol. The difference in transmission range directly impacted the performance of routing protocols in most cases. In the considered scenarios, the travel time and waiting time of the ferryboat affected the number of messages that expired before reaching the destination due to TTL. The total size of delivered messages maximized when the number of messages was the largest for small messages, while it was maximized when the number of messages was the smallest for large messages. This motivated us to seek an optimal segmentation (message size) in file transfer. Comparing the characteristics of the routing protocols, DO, MP, and PV2 use history information for the forwarding mechanism, but in slightly different ways, which results in better use of forwarding opportunities and in better performance for large messages. EP does not use such knowledge in its forwarding mechanism, so when the size of a message or the number of messages increases, the performance of EP deteriorates significantly. With large messages, the buffer storage likely becomes full quickly, which results in loosing chances of forwarding messages when two nodes meet. As we focused on a single source and a single destination in this chapter, we will investigate multiple sources/destinations scenarios in future work. We also need to examine spray-and-focus type routing schemes [6] in which message replication is intentionally suppressed. Based on the obtained results, our goal should be toward the consideration of how to dynamically and flexibly adjust and combine multiple forwarding techniques in response to a desired/given scenario and parameters.

Chapter 5

Spray Router with Node Location Dependent Remaining-TTL Message Scheduling in DTNs

In the island scenario, the source and destination nodes are located in separate areas (e.g., islands) connected by limited relay nodes (e.g., a ferry). The ferry periodically shuttles between the two islands and is a bottleneck for end-to-end delivery because it is the only way to convey messages between the islands. More specifically, the messages left behind must wait for the next ferry, which may take a substantial amount of time. Further, since the ferry takes time to make the trip, some messages may expire during the trip.

This chapter presents the spray-and-hop-distance-based with remaining-TTL consideration (SNHD-TTL) routing protocol, which is illustrated in Figure 5.1. This protocol combines the following three techniques: (1) binary spray for fast and limited message delivery, with the aim that each message spreads quickly (i.e., with small reduction in the remaining TTL) to a predefined number of nodes, preventing buffer full conditions; (2) hop distance to destination-based forwarding to prevent unnecessary message transmissions to nodes logically-located further from the destination, this feature actually prevents messages being forwarded in the opposite (wrong) direction between islands; and (3) node location dependent remaining-TTL message scheduling which gives priority to the message queue before forwarding to another node. This priority divides the message queue depending on node location and remaining TTL. Here, higher priority is given to messages that have small remaining TTLs that could reach the destination node. The subsections below provide further details regarding each component of this protocol.

The TTL, initially set by the source node, is a timer which limits the lifetime of a message in the network. When a message is transmitted from a node to another node, the messages TTL is updated by subtracting the time for which the messagehas been stored in the sending node (measured by its own clock), and thus it indicates the remaining lifetime of the received message. When the TTL value becomes 0 (i.e., expires), all copies stored in the network nodes are erased [1]. Note that global clock offset synchronization is not required, but a clock skew synchronization is required which is not strictly due to the timegranularity considered in DTN.

5.1 Binary Spray

The SNHD-TTL routing protocol employs the “spray phase” mechanism from binary Spray and Wait [8]. This protocol controls the number of messages transmitted by setting up the maximum number of copies created per messages, which can minimize the resource consumption (e.g., bandwidth and buffer storage). To initially spread each newly generated message from its source node to relay nodes while controlling the number of copies, binary spray is used in which a copy limit is defined as the permitted number of copies of a message during the spray phase. Each message has an initial copy limit L which is generated at its source node. For a message with a copy limit of N ($N > 1$) stored at node A, whenever node A encounters another node B which does not have that message, it is forwarded to node B and the message’s copy limit is changed to half its original value (i.e., $\lfloor N/2 \rfloor$) at both nodes A and B. For a message with a copy limit of 1 stored at node A, (instead of the “wait phase” in

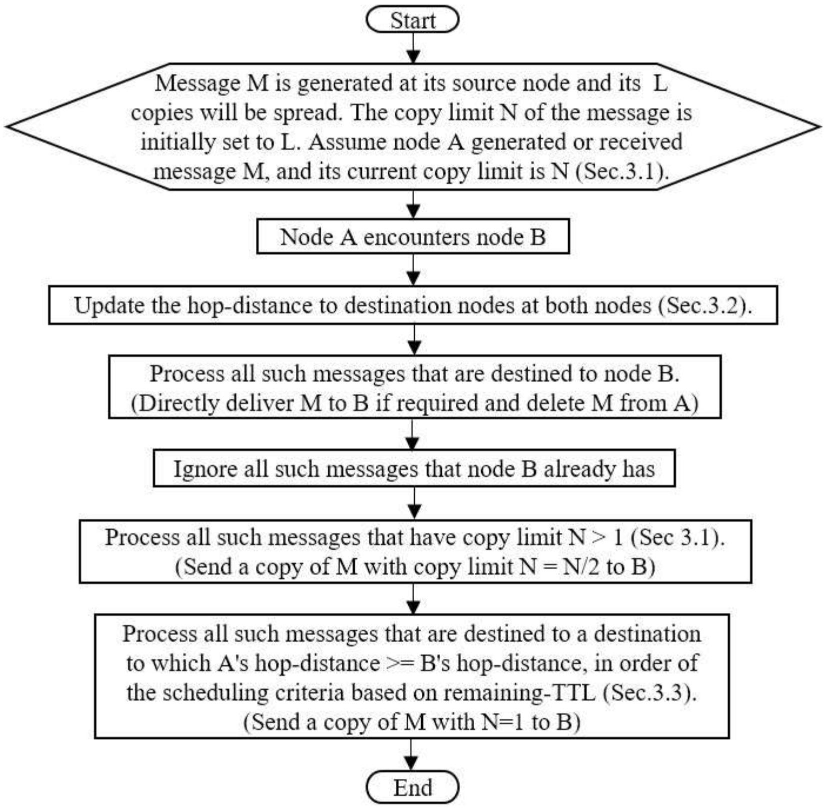


Figure 5.1: Flowchart of SNHD-TTL routing protocol

the Spray-and-Wait) SNHD-TTL forwards the message according to the hop distance-based forwarding mechanism described in the next subsection.

5.2 Hop Distance based Forwarding

After the binary spray phase, (i.e., when the copy limit of messages is 1), we use the hop distance to the destination node to determine how to forward that message in order to prevent unnecessary transmission. A node that periodically encounters the destination directly (i.e., a "good" nearest node) has the smallest hop distance value of 1. The update process for hop distance at node A, for example, is as follows. Node A's hop distance to the destination is initially set to "infinity". When node A encounters the destination node, node A will reset its hop distance value to 1. When node A encounters node B other than the destination, A's hop distance will be set so that it is not-greater than the one from "A's current hop distance" and "B's current hop distance plus 1". Messages stored at node A (and not stored at node B) will then be forwarded to node B if and only if node B has an equal or lower hop distance to the destination than that of node A.

5.3 Node Location Dependent Remaining-TTL Message - Scheduling

In our proposal, node location, that is the island at which the node runs, is considered to fit in heterogeneous and specific scenarios. Figure 5.2 shows a flowchart of our proposed message scheduling algorithm. Some global knowledge about the network, e.g., the statistics of message delivery time from each location, as shown in Figure 5.3(a) and 5.3(b), are used to define two variables, namely the expected minimum "normal" time for a message to reach its destination (W) and the expected maximum "normal" time to reach the destination (W'). Both of these values are dependent on its location. In Section 5.5.6, we will discuss how to decide W and W' in the system operation.

- W and W' value of large to small island (LtoS) scenario

  Car and bus node in the large island,

$$W = (50\text{-tile of } Li) + (50\text{-tile of } FT) + (50\text{-tile of } Si) \quad (5.1)$$

$$W' = (75\text{-tile of } Li) + (75\text{-tile of} FT) + (75\text{-tile of } Si) \quad (5.2)$$

  Station node in the large island,

$$W = (50\text{-tile of } FT) + (50\text{-tile of } Si) \quad (5.3)$$

$$W' = (75\text{-tile of } FT) + (75\text{-tile of } Si) \quad (5.4)$$

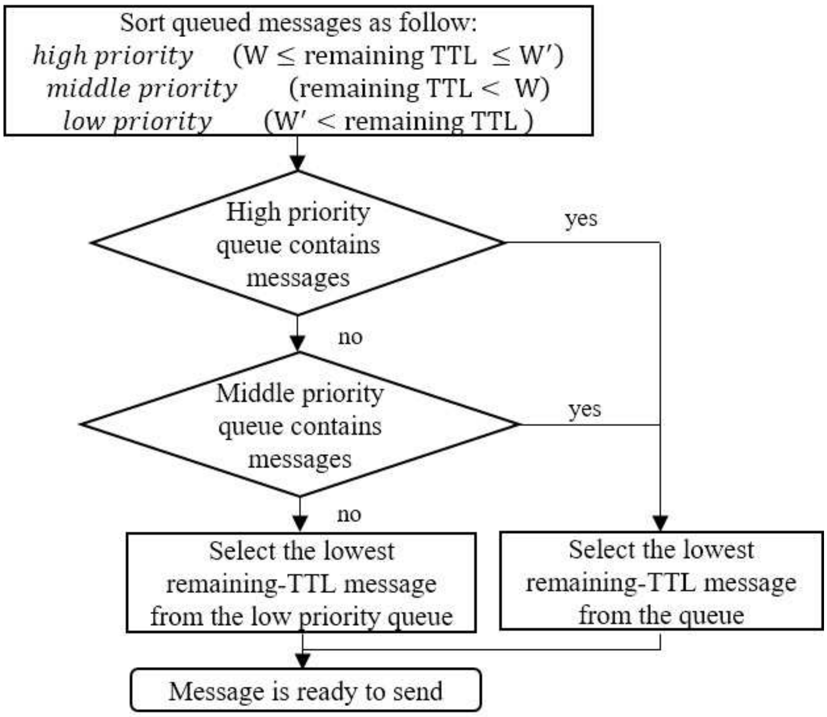


Figure 5.2: Flowchart of the Node Location Dependent Remaining-TTL message scheduling

Car, bus, and station node in the small island,

$$W = 50\text{-tile of } Si \tag{5.5}$$

$$W' = 75\text{-tile of } Si \tag{5.6}$$

- W and W' value of small to large island (StoL) scenario

  Car and bus node in the small island,

$$W = (50\text{-tile of } Si) + (50\text{-tile of } FT) + (50\text{-tile of } Li) \tag{5.7}$$

$$W' = (75\text{-tile of } Si) + (75\text{-tile of } FT) + (75\text{-tile of } Li) \tag{5.8}$$

  Station node in the small island,

$$W = (50\text{-tile of } FT) + (50\text{-tile of } Li) \tag{5.9}$$

$$W' = (75\text{-tile of } FT) + (75\text{-tile of } Li) \tag{5.10}$$

Car, bus, and station node in the large island,

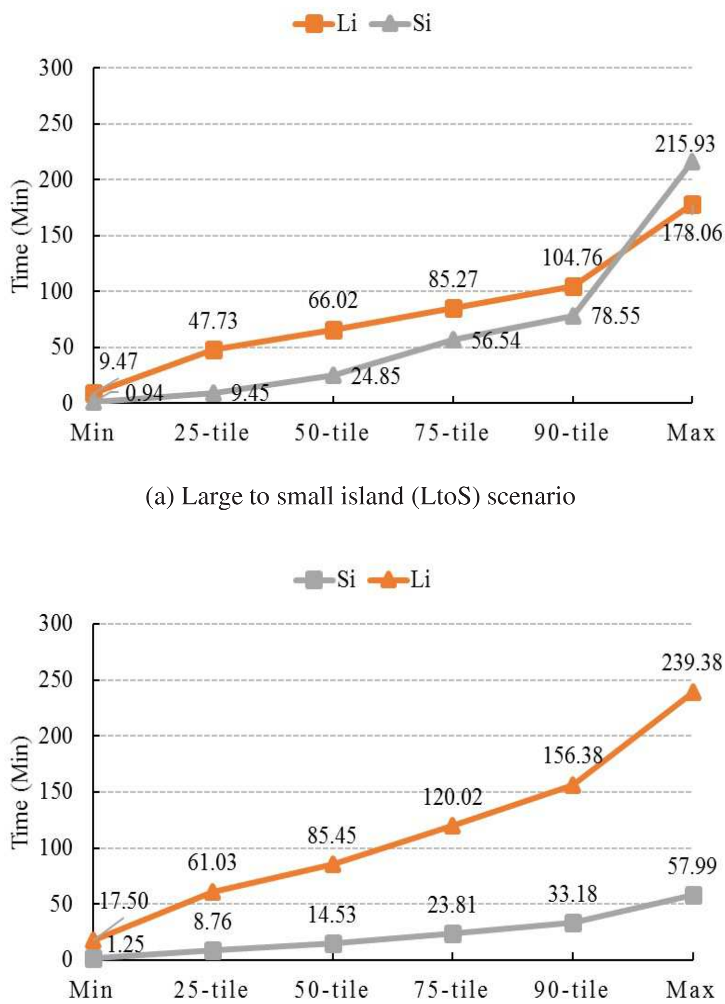
$$W = 50\text{-tile of } Li \tag{5.11}$$

$$W' = 75\text{-tile of } Li \tag{5.12}$$

Here, Li is the message delivery time between a stationary (source or destination) node and the ferry station on the large island, Si is the message delivery time between a stationary (source or destination) node and the ferry station on the small island. We use a 50-tile of the delivery time value as the minimum normal time to deliver a message from each location to the destination, and a 75-tile of the delivery time value as the maximum normal time. FT is the duration the ferry travels between the station on the small island and the station on the large island, including the waiting time at the stations. We define FT as a fixed value, the wait time in the stations is $[0, 30]$ min, and the travel (sailing) time is 15 min. So "the wait time + travel time" is $[15, 45]$. Then, 50-tile is expected to be about 30 min, and 75-tile about 38 min. By combining W and W' with remaining-TTL of each message, the message's priority in the contact duration is determined as follows: the priority is high if $W \leq$ remaining TTL $\leq W'$, middle if remaining TTL $< W$ and low if $W' <$ remaining TTL. Each message class (queue) is processed in order of its priority from high to low. In each message class, in order of message's remaining-TTL (lowest remaining-TTL first), the messages that pass the criteria of the hop distance-based forwarding phase are forwarded to the contacted node. When the buffer storage is full and a new message arrives, a "drop-oldest" policy is used to drop the oldest messages.

5.4 Evaluation Scenario

As shown in Figure 5.4, the scenario is based on the map-based model and simulated using *The Opportunistic Network Environment (ONE) Simulator* [28]. We considered a real-life



(a) Large to small island (LtoS) scenario

(b) Small to large island (StoL) scenario

Figure 5.3: Delivery time report of Epidemic Protocol with 819.2 MB and TTL 240 min

scenario in which two islands, Large island and Small island, are connected by a ferry between station nodes, with buses and cars as relay nodes and stationary nodes. They can be considered to be source and destination nodes on each of the islands. This scenario is modeled by considering a real situation in Indonesia, and a similar type of scenario can be seen in the literature as well. For example, [27] considered island-hopping experiments where a stationary node located in three geographically separated groups are connected by three mobile "traveler nodes". In our scenario, during the simulated 840 min period of time, ten mobile nodes (e.g., cars and buses) in the large island and six mobile nodes in the small island move on the map's roads with speeds from 5 to 30 km/h, between random location on each island to deliver messages from each destination node according to the message delivery scenario. The waiting time of the ferry on each island is about 30 minutes, and the traveling time (sailing) of the ferryboat between two islands is 15 minutes.

We assume the ferry and ferry station nodes on each island as a gateway node with a larger buffer size than the mobile node, which is essential so as not to make the gateway a bottleneck. Since the limitation of the ONE simulator which only supports 2,000 MB of maximum buffer storage size, we used the following in the scenario: 1:10 comparison ratio for the buffer size, each mobile node has a 200 MB buffer, then the gateway node has a 2,000 MB buffer. Later in Section 5.5.8 we also evaluate our proposed method with the increased buffer size ratio of 1:2 since it is close to reality.

The origin of the messages depend on the message delivery scenario. Messages are generated in a stationary source node located on an island and destined to a stationary destination node on the other island. In the LtoS scenario, the source is located on the large island, and in the StoL scenario, the source is located on the small island. The source node generates messages with size 0.4 MB, and various total sizes [204.8 MB, 409.6 MB, 819.2 MB, 1,638.4 MB, and 3,276.8 MB] within 480 min. To change the total size, we control the average time-interval of message generation. The message time-to-live (TTL) of 240 and 480 min are used for each simulation scenario. A larger value of TTL will have more chances for a message to reach its destination, while more messages stored in the network node's for long periods of time will potentially increase the consumption of resources (e.g., bandwidth and buffer space). To adapt the comparison ratio of the buffer size, we decreased the WiFi link interface with a transmission data rate of 1 Mbps and an omni-directional transmission range of 25 m as scaling. To evaluate our proposal with a different buffer-size and WiFi-rate relation, later in Section 5.5.8, we increase the transmission rate and transmission range as consid-

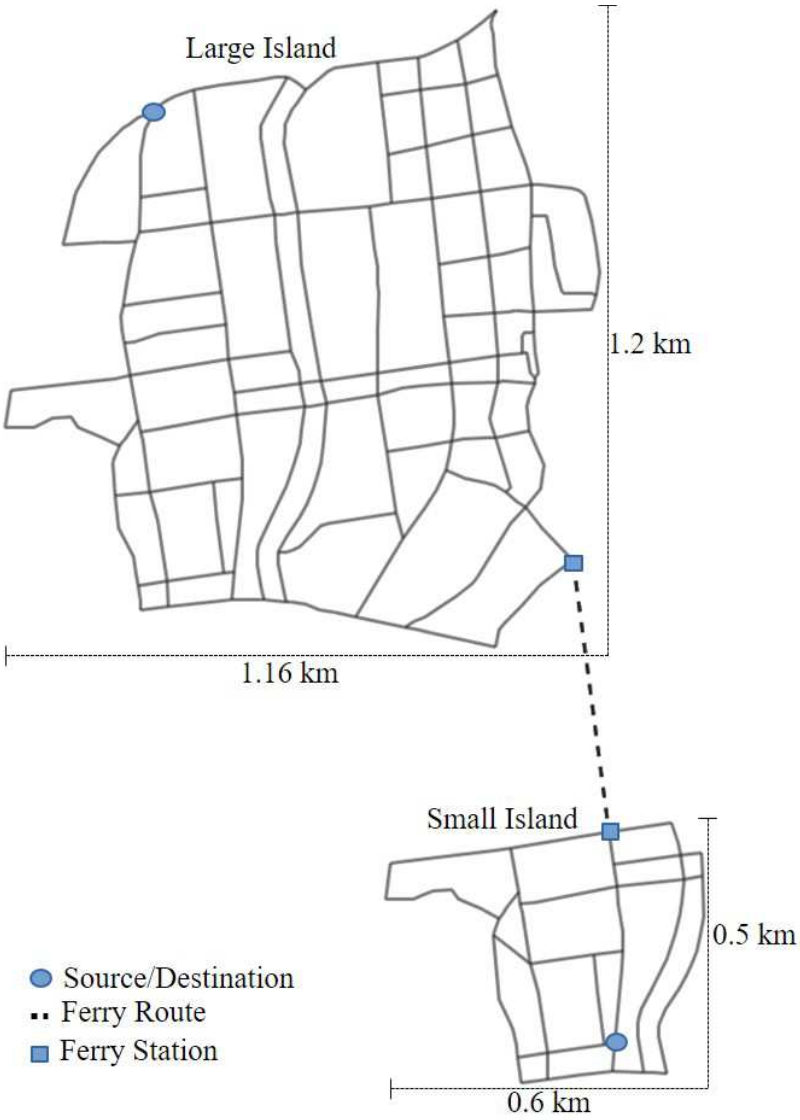


Figure 5.4: Simulation scenario: large island and small island connected by ferryboat

ered in [29] and [30] with the increased buffer size ratio of 1:2. In order to get meaningful comparison results, the simulation scenario was executed 10 times using different movement seeds. Each figure shows the average value calculated from these results.

As discussed previously, SNHD-TTL employs binary spray with a parameter of L and the remaining-TTL consideration with parameters of W and W'. As default values, we used

Table 5.1: Simulation parameters

Parameter	Value
Simulation time	840 min
Node buffer size	Car and Bus = 200 MB
	Station A and B, Ferry = 2,000 MB
Interface transmit speed and range	1 Mbps and 25 m
Message lifetime (TTL)	240 and 480 min
Node speed	Bus = 5-20 km/h
	Car = 10-30km/h
Total size (amount) of originally-generated messages	204.8 MB, 409.6 MB, 819.2 MB 1,638.4 MB, 3,276.8 MB
Message created duration	480 min from the beginning
Message size	0.4 MB
Warm up time	30 min

an L of 3, and W and W' are obtained from statistics derived from message delivery time of EP with 819.2 MB of the total size of generated messages. Later in Sections 5.4.5 and 5.4.6, we examine and discuss the impact of these parameters on SNHD-TTL's performance. Table 5.1 summarizes the simulation parameters used in our evaluations.

5.5 Simulation Results

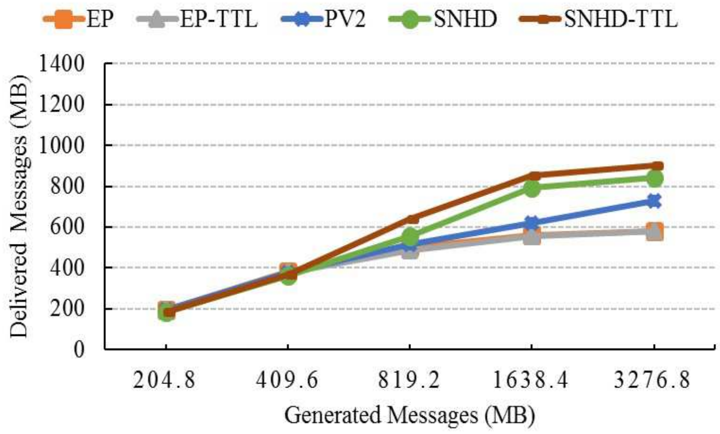
The performance of the SNHD-TTL routing protocol is compared through simulation against two popular DTN routing protocols, EP and PV2, plus two comparative routing protocols, EP-TTL (the EP protocol integrated with node location dependent remaining-TTL message scheduling), and SNHD (our proposed protocol without node location dependent remaining-TTL message scheduling). We used three performance metrics: the total size of delivered messages, overhead ratio, and average latency. The aim of our simulation study is to understand the impact of combining the considered techniques (i.e., binary spray, hop distance-based forwarding, and node location dependent remaining-TTL message scheduling) on improving the performance of DTN routing. We also evaluate the impact of increasing the number of nodes in each island, varying the number of copies L in the spray phase of SNHD-TTL, and sensitivity of W and W' values as obtained from the statistics of the message delivery time on the performance of SNHD-TTL.

5.5.1 The Total Size of Delivered Messages

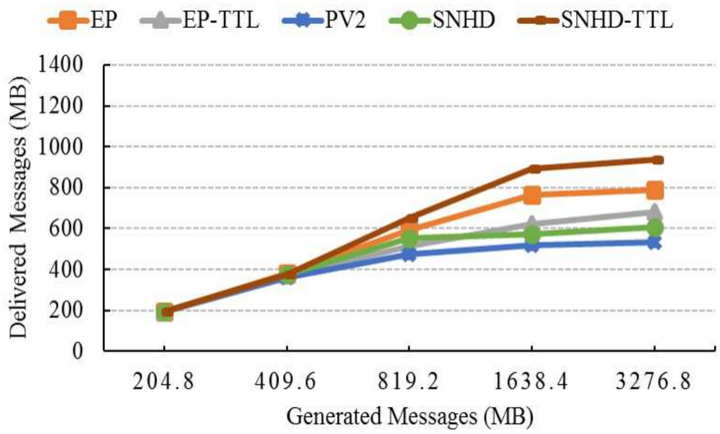
The total size of delivered messages is defined as the size of the message multiplied by the number of messages successfully delivered to the destination during the simulation. Figures 5.5(a) and 5.5(b) show the total size of delivered messages with a TTL of 240 min under the LtoS and StoL message delivery scenarios. As the total generated size (i.e., the x-axis in the figures) increases, the network becomes congestion. In non- or weakly congested states, the performance of each protocol is similar. On the other hand, in congested states, a significant performance difference among protocols is seen. For the TTL 240 min performance of SNHD-TTL both message delivery scenarios are almost the same and perform the best across all protocols. In the LtoS scenario, EP-TTL and EP achieved lower performance, while in the StoL scenario, EP achieved better performance than EP-TTL, PV2, and SNHD for the 1,638.4 MB and 3,276.8 MB cases.

Figures 5.6(a) and 5.6(b) show the total size of delivered messages with a TTL of 480 min, which indicate performance among all of protocols depends on message delivery scenarios. Compared with Figures 5(a) and 5(b), in both LtoS and StoL scenarios, the performance advantage of SNHD-TTL to other protocols is much greater.

In summary, except in cases of non- or weakly congested states, SNHD-TTL clearly outperformed other protocols irrespective of the delivery scenarios (StoL or LtoS) and TTL (240 min or 480 min).



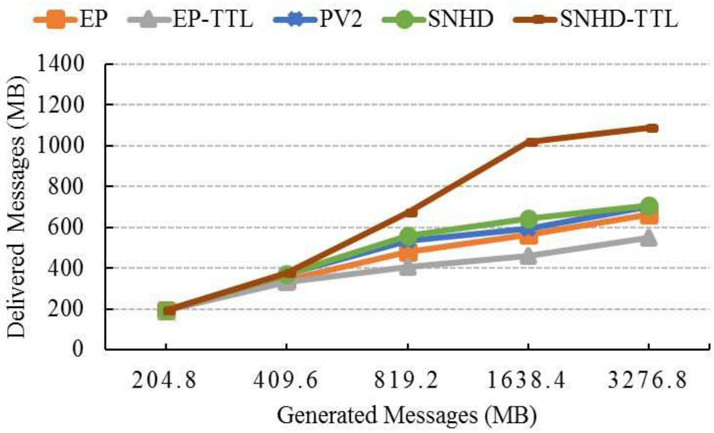
(a) Large to small island (LtoS) scenario



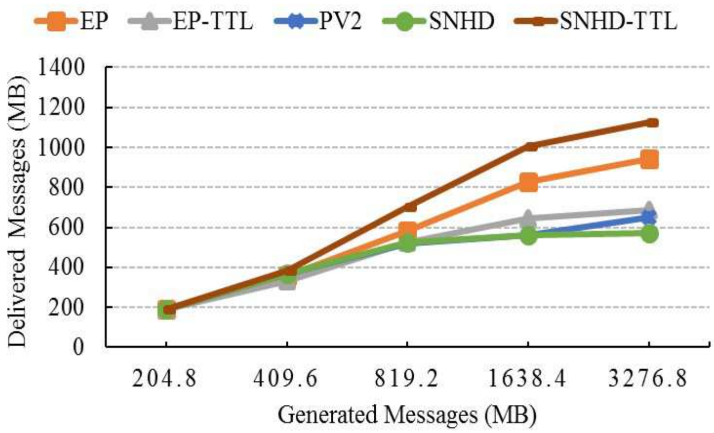
(b) Small to large island (StoL) scenario

Figure 5.5: The total size of delivered messages with TTL 240 min

For buffer management, we compared EP with EP-TTL and SNHD with SNHD-TTL. For EP-TTL, we found that this method did not significantly improve performance as compared with EP, even for the StoL scenario in the 1638.4 MB and 3276.8 MB cases. For the LtoS scenario with a TTL value of 480 min, the performance of original EP was better than EP-TTL. Conversely, our proposed message scheduling had an impact on the performance of SNHD. More specifically, SNHD-TTL was better as compared with SNHD.



(a) Large to small island (LtoS) scenario



(b) Small to large island (StoL) scenario

Figure 5.6: The total size of delivered messages with TTL 480 min

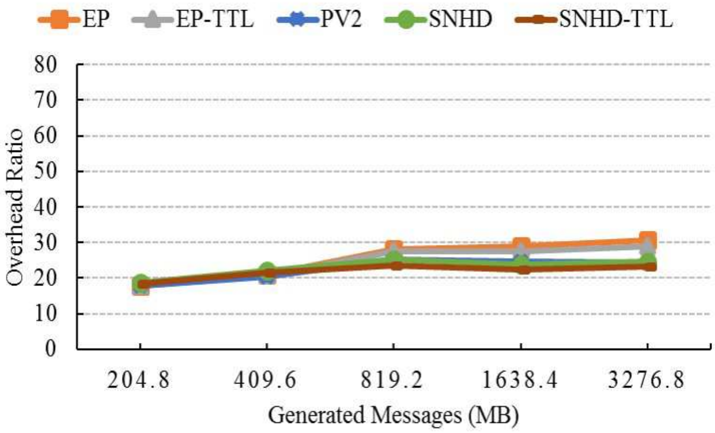
5.5.2 Overhead Ratio

The overhead ratio is based on how many additional messages were relayed for each delivered message. This is reflected as transmission efficiency. Figures 5.7(a) and 5.7(b) present the overhead ratio of LtoS and StoL scenario with TTL 240 min. The overhead increased as the total size of generated message increased, but each protocol behaved differently. In the LtoS scenario, the overhead ratio of all routing protocols in the congested state fluctuated about 20 to 30 messages, while in the StoL scenario the fluctuation is about 35 to 50 messages. SNHD-TTL shows lower overhead than the other protocols at 819.2 MB. There were more congested cases especially in StoL scenario. The overhead ratio for TTL 480 min is illustrated in Figures 5.8(a) and 5.8(b). Compared with Figures 5.7(a) and 5.7(b), generally, a longer TTL (480 min) results in a larger overhead, except for the no congestion case. The characteristics seem more complicated depending on the algorithm of each protocol and message delivery scenario. SNHD-TTL also shows lower overhead than the other protocols, especially in the LtoS scenario.

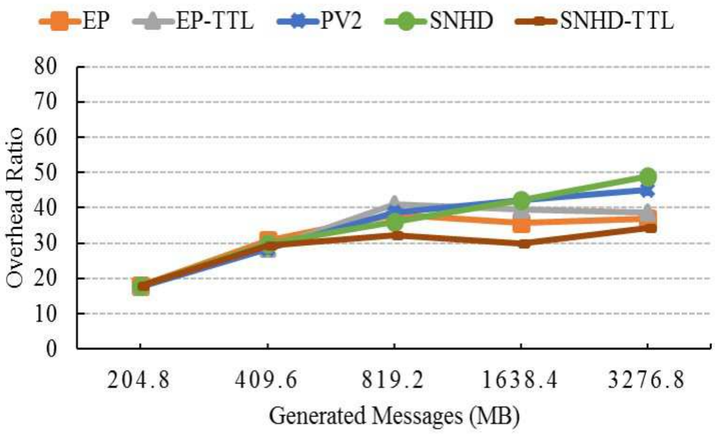
Our implementation of binary spray, hop distance-based forwarding, and node location dependent remaining-TTL message scheduling in SNHD-TTL, decreased the number of copies of each message as compared with the other routing protocols. As explained in Section 5.3, SNHD-TTL gives priority to messages which are very young and that are stored only at a few nodes (less than L) are first. Messages with a moderate remaining-TTL in relation with its current location are second, messages with a short remaining-TTL are next, and messages with sufficient remaining-TTL are last. This would result in an effective use of limited resources (i.e., the number of messages to be forwarded within each valuable contact duration) in congested states. On the other hand, SNHD implements binary spray and hop distance-based forwarding, and EP-TTL implements node location dependent remaining-TTL message scheduling. Both of these failed to achieve low overhead. In some cases, they have a higher overhead than the other protocols, which implies a combination of these three techniques is necessary to achieve effective message delivery.

5.5.3 Average Latency

Figures 5.9(a) and 5.9(b) show the average latency for TTL values of 240 min and Figures 5.10(a) and 5.10(b) show the average latency for TTL values of 480 min under both message delivery scenario. The average latency is the average time difference between the message generation time at the source and the message received time at the destination over



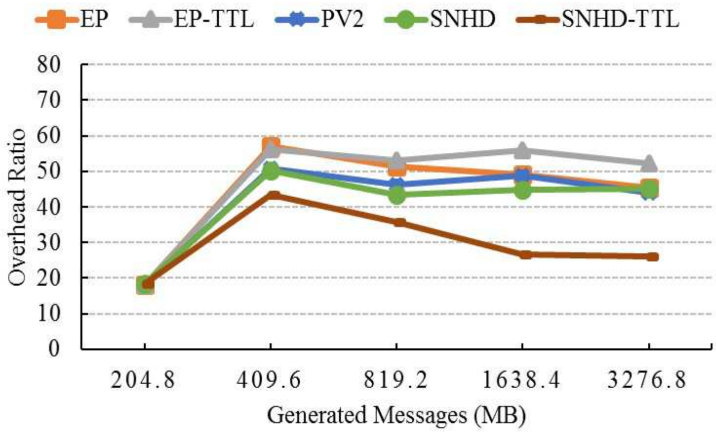
(a) Large to small island (LtoS) scenario



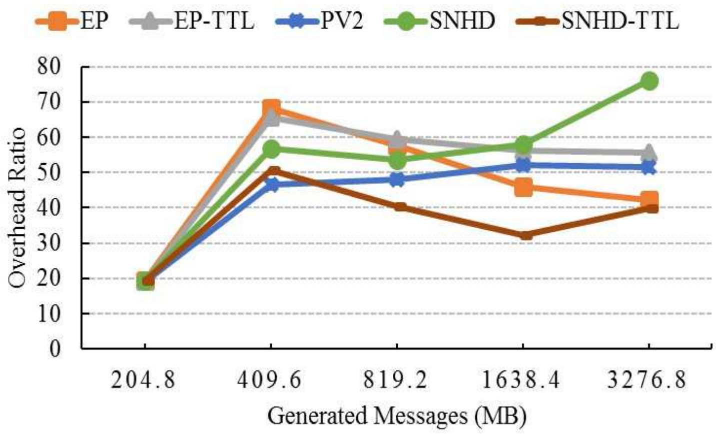
(b) Small to large island (StoL) scenario

Figure 5.7: Overhead ratio with TTL 240 min

all successfully delivered messages. Increasing the message TTL value increased the average latency of all routing protocols. In congested states, SNHD-TTL exhibited a higher latency than the other protocols while it significantly outperformed other protocols in terms of the total size of delivered messages. Increasing the message TTL from 240 min to 480 min increased the average latency of all routing protocols, especially for SNHD-TTL, which increased from approximately 200 min to 420 min. In the StoL scenario, the average latency



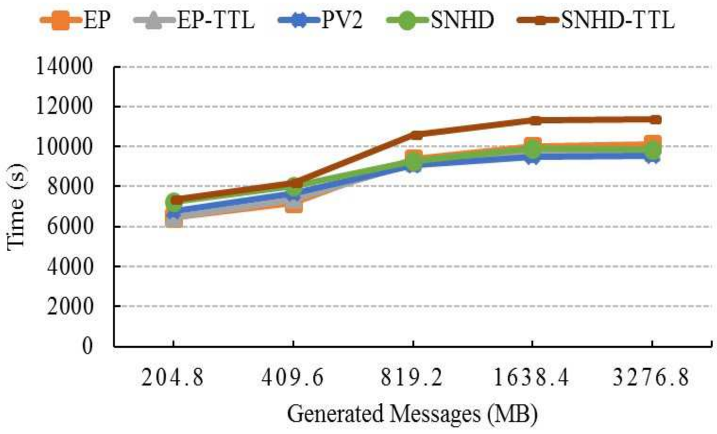
(a) Large to small island (LtoS) scenario



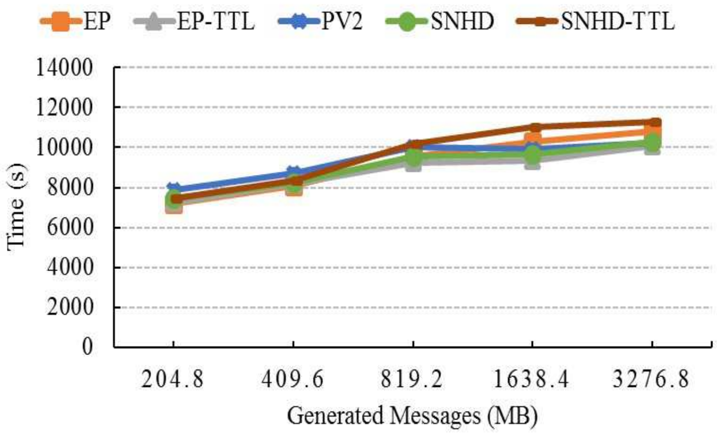
(b) Small to large island (StoL) scenario

Figure 5.8: Overhead ratio with TTL 480 min

of all protocols except for SNHD-TTL achieved almost similar performance. It was about 130 min to 180 min when TTL is 240 min, and about 130 min to 300 min when TTL is 480 min. Then in the LtoS scenario, the difference among protocols varies, depending on the size of the generated messages. For example, EP has a lower latency in the 409.6 Mb case and then becomes higher than the other protocols except for SNHD-TTL in the 819.2 MB and 1638.4 MB cases when TTL is 240 min.



(a) Large to small island (LtoS) scenario

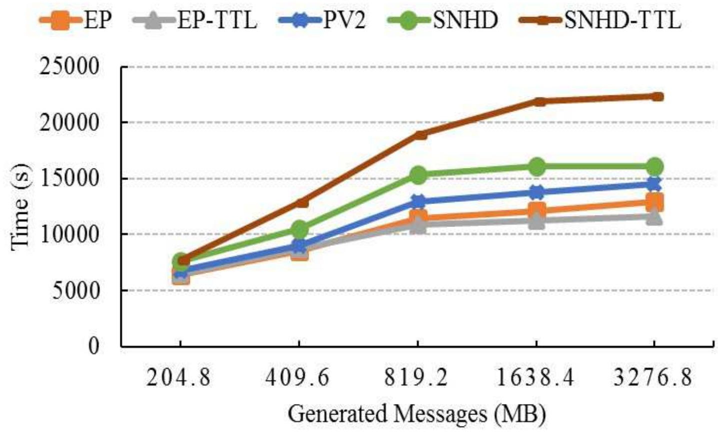


(b) Small to large island (StoL) scenario

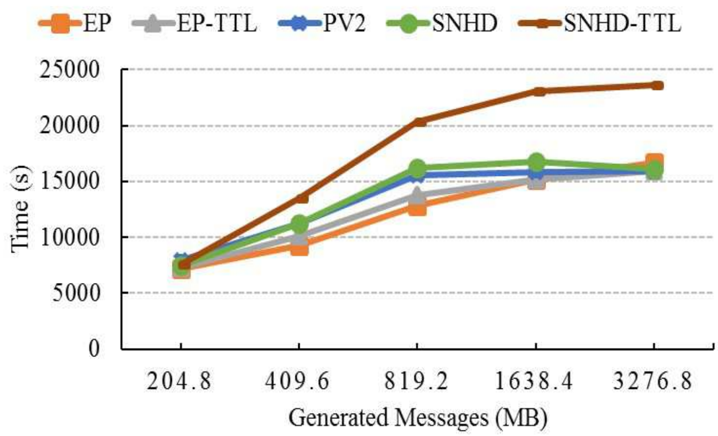
Figure 5.9: Average latency with TTL 240 min

5.5.4 Impact of Increasing Number of Nodes in Each Island on The Total Size of Delivered Messages

In this evaluation, we increased the number of nodes on both islands. In the large island, the number of nodes is increased from 10 (6 cars and 4 buses) to 15 (9 cars and 6 buses), then in the small island it is increased from 5 (3 cars and 2 buses) to 9 (6 cars and 3 buses). Figures



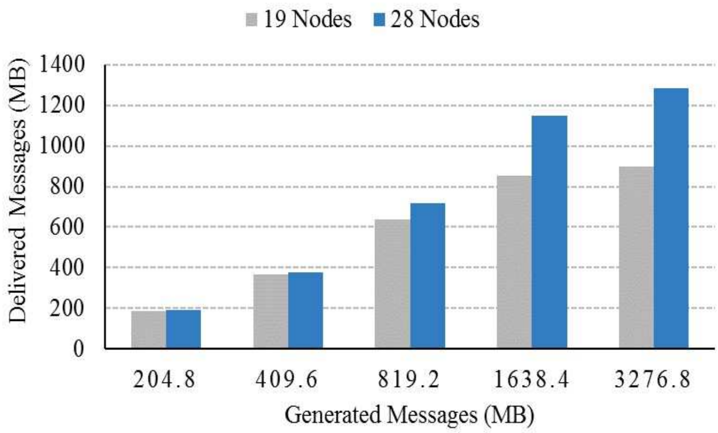
(a) Large to small island (LtoS) scenario



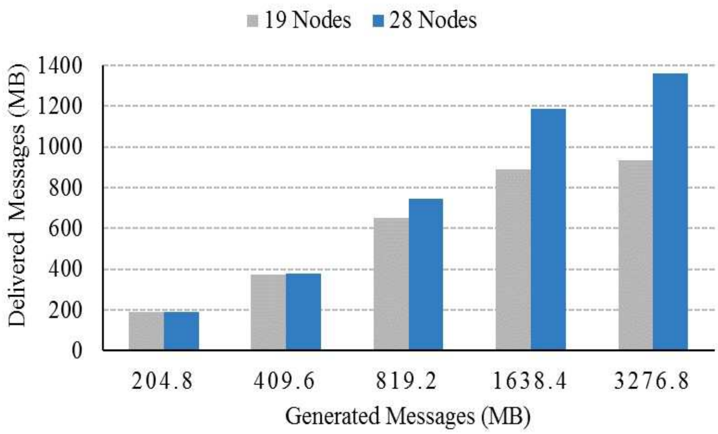
(b) Small to large island (StoL) scenario

Figure 5.10: Average latency with TTL 480 min

5.11(a) and 5.11(b) show the total size of delivered messages as the number of nodes increases. In general, increasing the number of nodes will increase the performance compared with the default number of nodes. Increasing the number of nodes increased the number of messages that can be stored in the buffer storage on the network as well as the number of messages that can be exchanged by contacts between nodes. This decreased the delay time of messages to reach the destination node. As shown in Figures 5.12(a) and 5.12(b), the



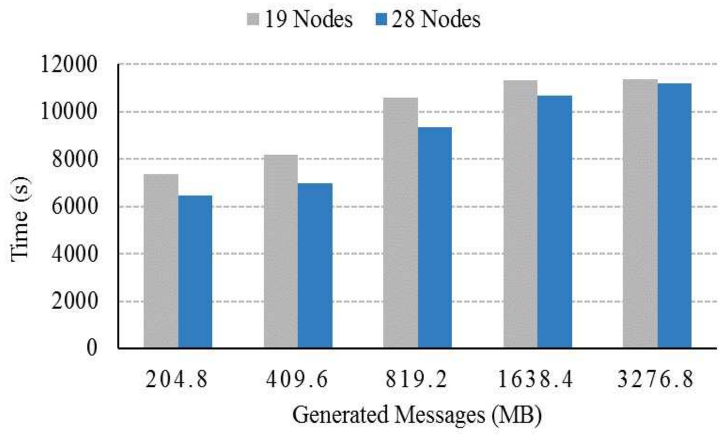
(a) Large to small island (LtoS) scenario



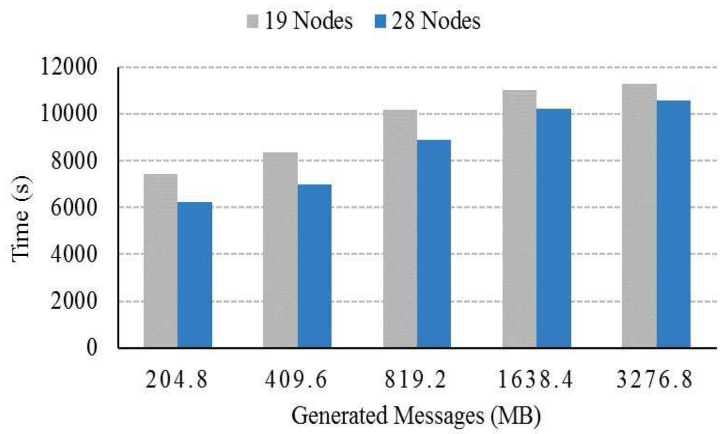
(b) Small to large island (StoL) scenario

Figure 5.11: Impact of increasing the number of nodes on the total size of delivered messages

average latency of 28 nodes is lower than 19 nodes in the LtoS and StoL scenarios.



(a) Large to small island (LtoS) scenario



(b) Small to large island (StoL) scenario

Figure 5.12: Impact of increasing the number of nodes on the average latency

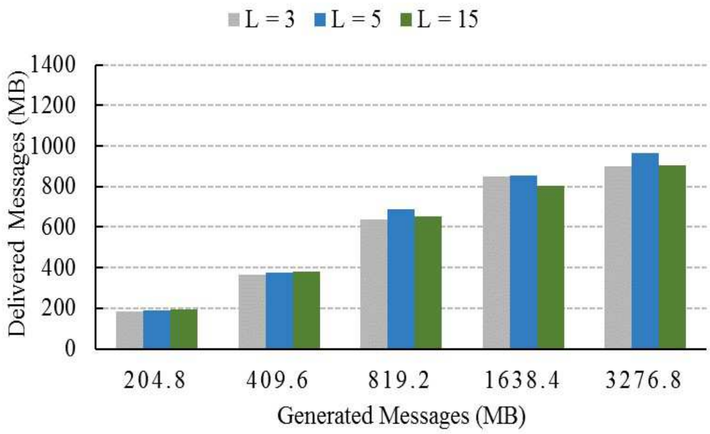
5.5.5 Impact of Varying the Number of copies (L) on The Total Size of Delivered Messages

As shown in Figures 5.13(a) and 5.13(b), we evaluated the impact of the number of generated message copies (L) in the spray phase on the performance of SNHD-TTL in terms of the total size of delivered messages. In the LtoS scenario, varying L had a significant impact

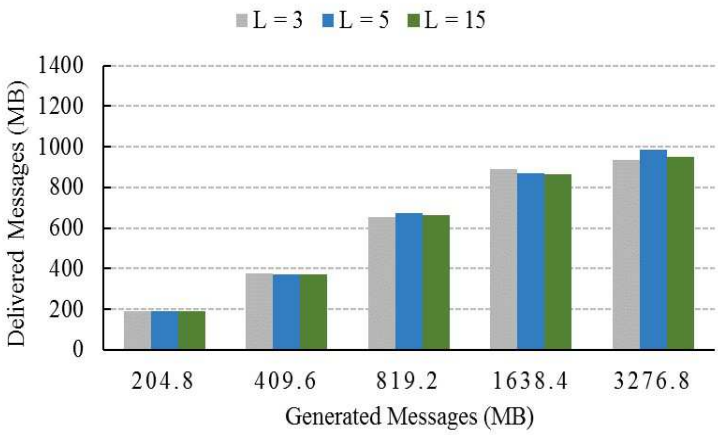
Table 5.2: W and W' value from EP

Msg. Gen. Size	Value	Li Node	Station Li	Si Node
204.8 MB	**W**	69.36	37.01	7.01
	W'	89.47	47.51	9.51
409.6 MB	**W**	81.10	37.46	7.46
	W'	107.79	48.33	10.33
819.2 MB	**W**	120.87	54.85	24.85
	W'	179.80	94.54	56.54
1638.4 MB	**W**	175.81	105.19	75.19
	W'	275.17	171.37	133.37
3276.8 MB	**W**	184.80	110.89	80.89
	W'	309.12	210.42	172.42

in cases where the size of generated messages totaled 819.2 MB or more. Note that the total size of delivered messages for all L values was almost the same for the cases from 204.8 MB to 409.6 MB, because the network capacity was large enough for all messages. When a congested state occurred, the larger number of copies caused a decrease in performance, because as L increased, the number of message transmissions also increased. Then in the StoL scenario, the total size of delivered messages with different L values achieved similar performance except in the 3,276.8 MB case, where small L values achieved better performance than the other values. Figures 5.14(a) and 5.14(b) show the impact of the L values on the average latency. In the LtoS scenario the number of L values significantly affected the average latency. Increasing the L values will decrease the average latency while in the StoL scenario the average latency is almost the same as all of the L values.



(a) Large to small island (LtoS) scenario

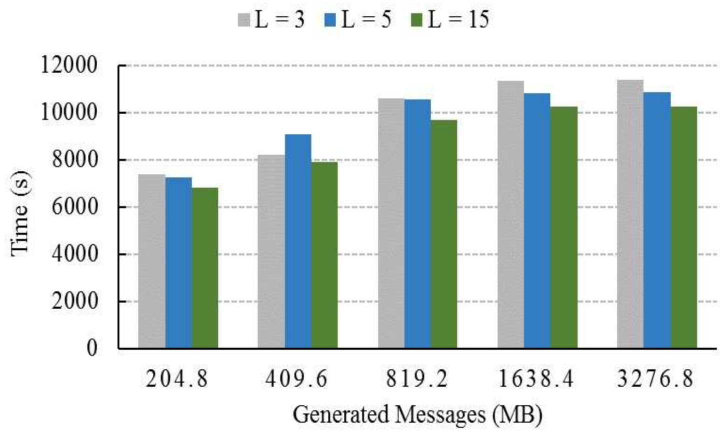


(b) Small to large island (StoL) scenario

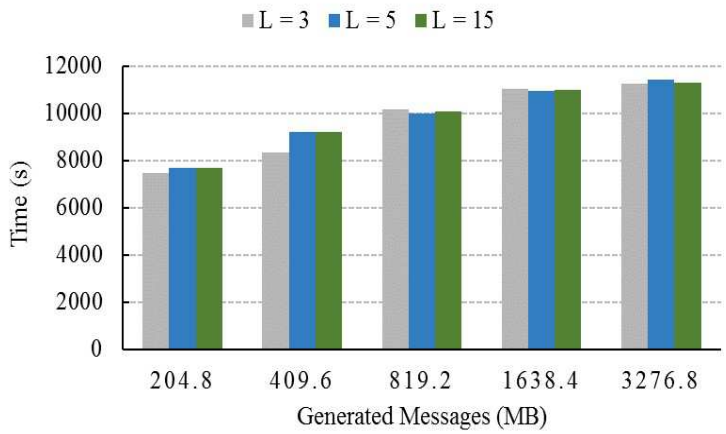
Figure 5.13: L impact on the total size of delivered messages

5.5.6 Impact of W and W' on SNHD-TTL's performance

Node location dependent remaining-TTL message scheduling used the statistics of delivery time in order to determine W and W' values. In the previous subsections, we used statistics from the delivery time of EP with 819.2 MB of the total size of generated messages to determine W and W' to serve as the baseline. We assume they can be roughly estimated beforehand from information obtained by some means, e.g., simulations or real field node



(a) Large to small island (LtoS) scenario



(b) Small to large island (StoL) scenario

Figure 5.14: L impact on the average latency

measurements.

Table 5.2 provides W and W' values according to the total size of generated messages which are calculated from the delivery time report in Figure 5.3 using the formula in Section 5.3 “Msg. Gen. Size” column contains information about the total size of the originally generated messages. The “Li Node” column contains W and W' values for the mobile node on the large island. The “Station Li” column contains W and W' values for the station node on the large island. The "Si Node" column contains W and W' values for the station node and the mobile node on the small island.

For calculating the LtoS scenario, from Figure 5.3 we get the 75-tile and 50-tile values for the large island as (Li) = 85.27 min and 66.02 min respectively. Then for the small island, we have (Si) = 56.54 min and 24.85 min respectively. Then for the ferry traveling time (FT) we used fixed values of 38 min for the 75-tile, and 30 min for the 50-tile which are determined based on the traveling time and waiting time of the ferry on each island. From each formula in Section 5.3, we get W and W' of EP 819.2 MB as follows:

- Li Node, using formulas (1) and (2)

$$W = 66.02 + 30 + 24.85 = 120.87$$
$$W' = 85.27 + 38 + 56.54 = 179.80$$

- Station Li, using formulas (3) and (4)

$$W = 30 + 24.85 = 54.85$$
$$W' = 38 + 56.54 = 94.54$$

- Si Node, using formulas (5) and (6)

$$W = 24.85$$
$$W' = 56.54$$

In this subsection, we show the impact of W and W' values on the message delivery performance, and discuss how to find and calibrate appropriate W and W' values. As shown in Table 5.3, new W and W' values are determined from the statistics of the message delivery time of SNHD-TTL as obtained by simulation using the W and W' values for the case of 819.2 MB from Table 5.2. Then, as shown in Table 5.4, different new W and W' values are determined from the statistics of the message delivery time of SNHD-TTL as obtained by the simulation using previously determined W and W' values for each message generated size case from Table 5.3. For example, we simulate SNHD-TTL with the 204.8 MB message generated size using W and W' values for the case of 204.8 MB in Table 5.3. We compare the total size of delivered messages of SNHD-TTL using different W and W' values. In Figures 5.15(a) and 5.15(b), EP409, EP819, and EP1638 mean SNHD-TTL using W and W' values obtained from the message delivery time statistics of EP in each of 409.6 MB, 819.6 MB and 1638.4 MB cases in Table 5.2, respectively. Those cases are intended to represent a static SNHD-TTL that uses the same W and W', irrespective of message generated sizes, i.e., congestion states. Note that EP819 is equivalent to the default SHND-TTL as evaluated in previous subsections. SNHDTTL(1) and SNHDTTL(2) mean the SNHD-TTL using the W and W' values obtained from SNHD-TTL in each corresponding message generated size case as shown in Tables 5.3 and 4.4, respectively. Those cases are intended to represent an adaptive SNHD-TTL that uses the different W and W' in response to message generated sizes, (i.e., congestion states) and thus we call them SNHDTTL-adaptive.

In the LtoS scenario, as shown in Figure 5.15(a), if the message generated size is small, (i.e., 204.8 MB and 409.6MB cases) the performance is not affected by W and W'. However, when the message generated size is large, EP1638 achieved the lowest performance. EP819 achieved lower performance than EP409, SNHDTTL(1), and SNHDTTL(2) in the 638.4 MB and 3276.8 MB cases. SNHDTTL(1) and SNHDTTL(2) achieved the best performance. In the StoL scenario as shown in Figure 5.15(b), when the message generated size is small, (i.e., 204.8 MB, 409.6 MB, and 819.2 MB cases) the performance is not affected by W and W'. EP409 achieved the lowest performance when the message generated size is large, (i.e., 1,638.4 MB and 3,276.8 MB cases). SNHDTTL(1) showed slightly lower performance than EP819, EP1638 and SNHDTTL(2) in the 1,638.4 MB case.

These results indicate that the use of the same W and W' independent of message generated sizes may cause performance degradation in some cases and it is difficult to determine a single best pair of W and W' (i.e., EP409, EP819, and EP1638). In contrast,

Table 5.3: W and W' value from SNHDTTL using W and W' value in case with 819.2 MB case in Table 5.2

Msg. Gen. Size	Value	Li Node	Station Li	Si Node
204.8 MB	**W**	70.66	38.24	8.24
	W'	93.08	51.24	13.24
409.6 MB	**W**	74.93	37.19	7.19
	W'	101.70	48.20	10.20
819.2 MB	**W**	104.13	38.79	8.79
	W'	152.44	52.59	14.59
1638.4 MB	**W**	140.56	39.77	9.77
	W'	181.62	53.53	15.53
3276.8 MB	**W**	148.53	43.29	13.29
	W'	195.86	60.22	22.22

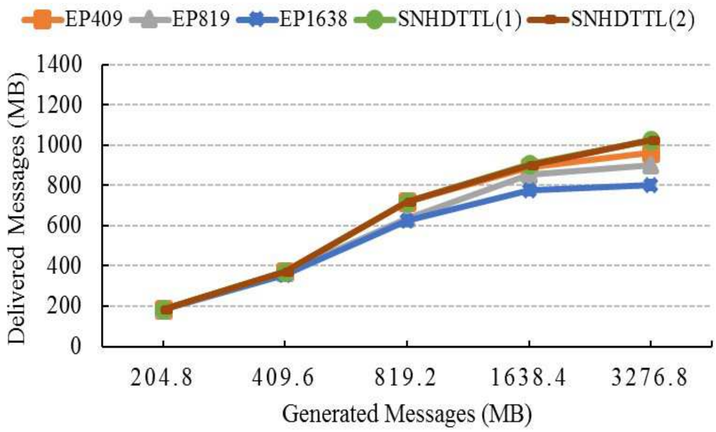
SNHDTTL(1) and SNHDTTL(2), that is SNHDTTL-adaptive, showed similar and stable performance. In addition, in some cases (StoL scenario in the 1,638.4 MB and 3,276.8 MB cases), SNHDTTL(2) achieved better performance than SNHDTTL(1). Therefore, an adaptive calibration of W and W' by updating them during operation should be considered. The statistics of message delivery time is required, to determine W and W' for each location. Sharing this information among nodes in an online manner is also needed. This could be possible by recording the history of TTL updates in all or some messages, monitoring them at stationary landmark nodes (the ferry stations and the destination in our scenario), and distributing this information, for example.

Table 5.4: W and W' value from SNHDTTL using W and W' value in Table 5.3

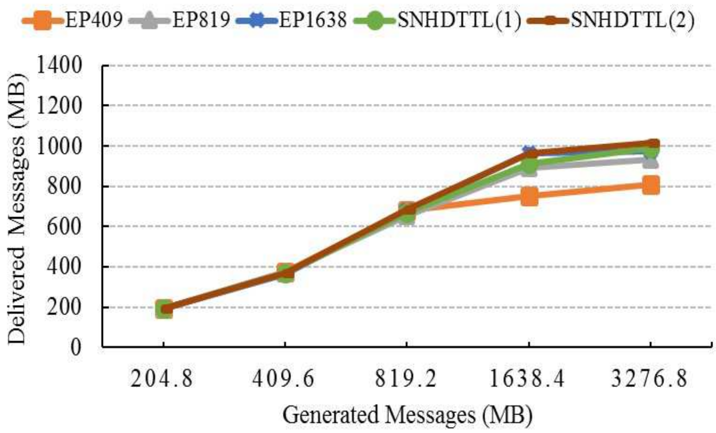
Msg. Gen. Size	Value	Li Node	Station Li	Si Node
204.8 MB	**W**	91.23	39.66	9.66
	W'	129	47.52	9.52
409.6 MB	**W**	104.08	38.13	8.13
	W'	155.88	49.81	11.81
819.2 MB	**W**	109.05	42.82	12.82
	W'	260.20	159.67	121.67
1638.4 MB	**W**	131.55	47.42	17.42
	W'	362.63	228.25	190.25
3276.8 MB	**W**	153.38	46.12	16.12
	W'	229.22	77.80	39.80

5.5.7 Impact of Increasing the Size of Island

This evaluation shows the impact of increasing the size of the island on the performance of all routing protocols. We increased the island size by using two larger maps that are enlarged by 2x and 3x from the original map as shown in Figure 5.4, respectively, and set the scenario parameters by 480 min of TTL value, 819.2 MB of the total size of generated messages and increasing the number of nodes from 19 nodes in the original scenario to 28 nodes. We determined the W and W' values according to each island size using message delivery reports of EP 819.2 MB. Figures 5.16(a) and 5.16(b) show the impact of increasing the size of the island on the total size of delivered messages. In general, as the size of the island increases, the performance of all routing protocols decreases and, at the same time, the advantage of our proposed SNHDTTL protocol using a single (W, W') also decreases even though it still works with a better or almost equal performance to other protocols. These results suggest, in larger island scenarios, we need to consider not only refining the selection of (W, W') but



(a) Large to small island (LtoS) scenario

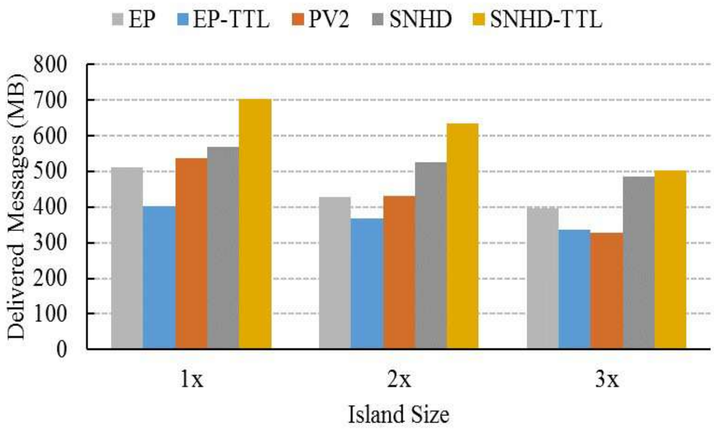


(b) Small to large island (StoL) scenario

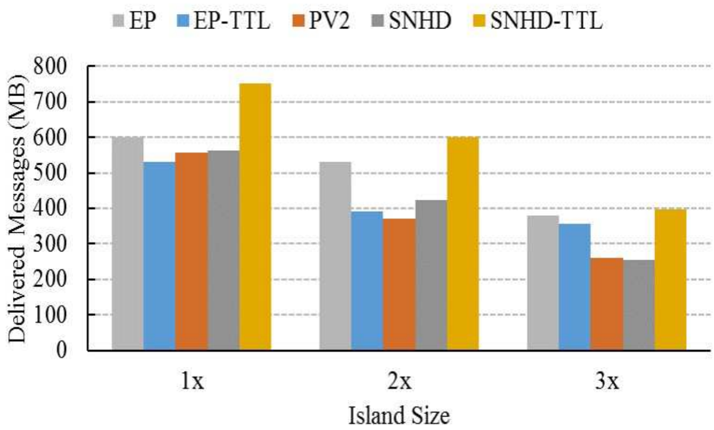
Figure 5.15: W and W' impact on the total size of delivered messages

introducing another refinement such as area partitioning.

Increasing the size of the island also affects the average latency as shown in Figures 5.17(a) and 5.17(b). When the island size increased 3x the average latency of all protocols also increased and become similar. These results indicate the difference between SNHDTTL and the other protocols will become smaller for larger island scenarios.



(a) Large to small island (LtoS) scenario

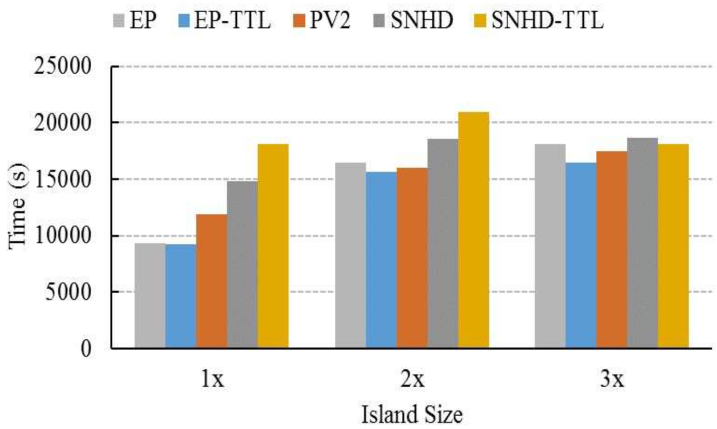


(b) Small to large island (StoL) scenario

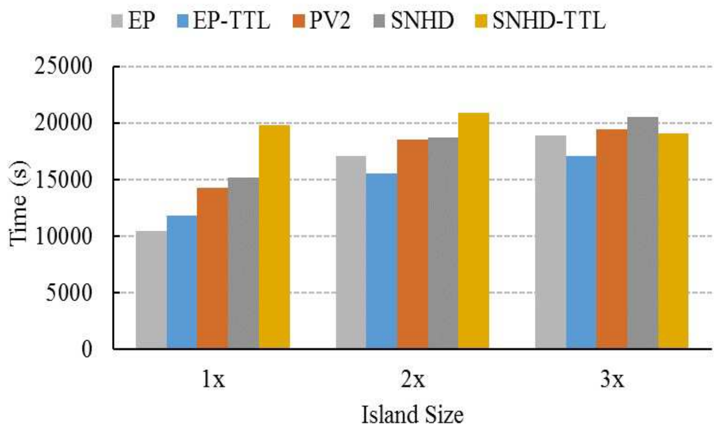
Figure 5.16: The size of island impact on the total size of delivered messages

5.5.8 Impact of Increasing Buffer Size and WiFi Transmit Rate and Range

In Section 5.4, we discussed about our simulation scenario. Due to the limitation of the maximum buffer size in the ONE simulator, we used a comparison ratio 1:10 for the buffer size of nodes (i.e., 2,000 MB for the gateway nodes, and 200 MB for mobile nodes), with



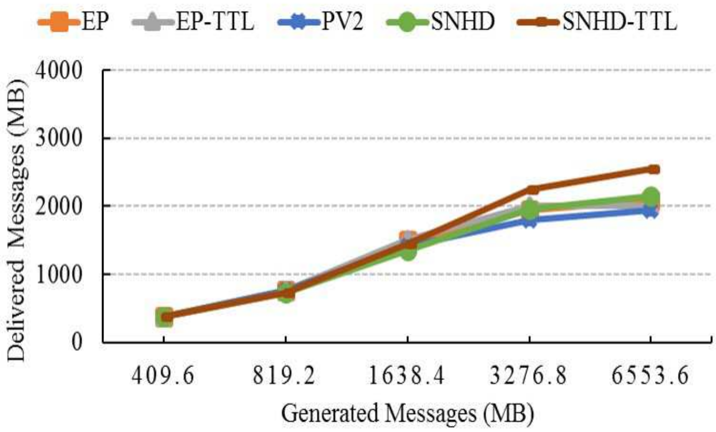
(a) Large to small island (LtoS) scenario



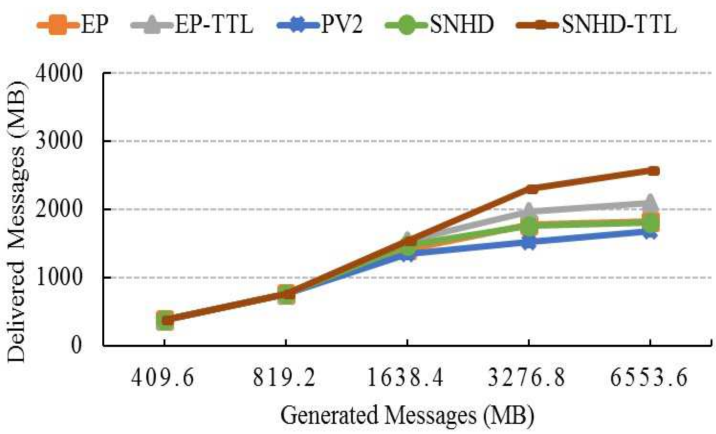
(b) Small to large island (StoL) scenario

Figure 5.17: The size of island impact on the average latency

a WiFi transmission rate and range of 1 Mbps and 25 m, respectively. In this section we discuss about the impact of increasing the buffer size ratio and WiFi transmit rate and range. We decreased the comparison ratio of buffer size from 1:10 to 1:2 (i.e., gateways nodes is 2,000 MB and mobile nodes is 1,000 MB), and increased the WiFi transmission rate and range to 4.5 Mbps and 30 m, as considered in [29], and [30]. We also omitted 204.8 MB and added 6,553.6 MB as the largest of the total size of generated messages. Since a congestion



(a) Large to small island (LtoS) scenario

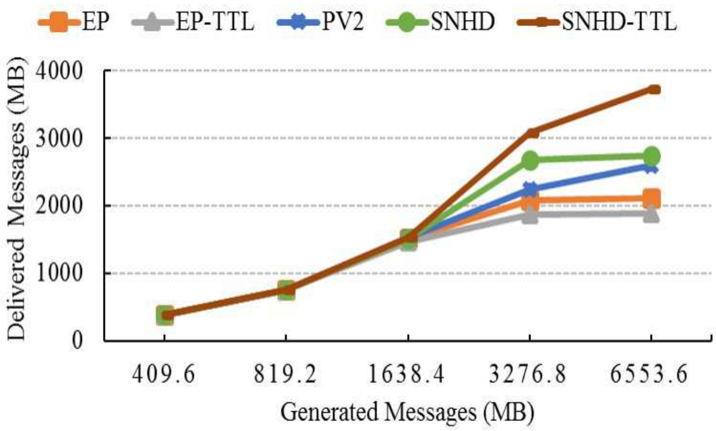


(b) Small to large island (StoL) scenario

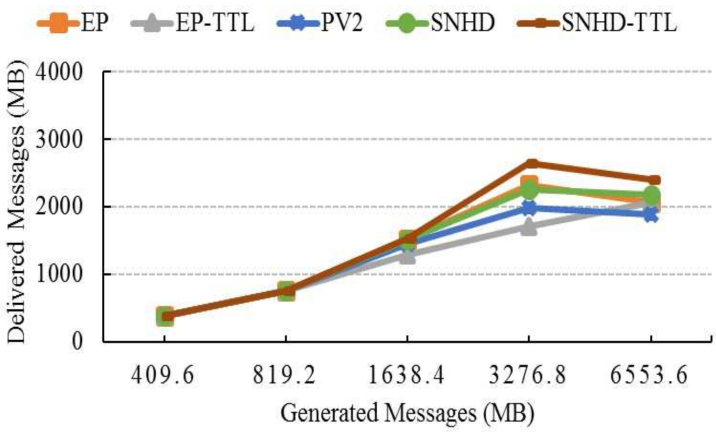
Figure 5.18: Buffer size and WiFi transmit rate and range increasing impact on the total size of delivered messages TTL 240 min

state of this new scenario occurred when the total size of generated messages was 3,276.8 MB, the W and W' values are determined by message delivery report of EP 3,276.8 MB.

Increasing the buffer size and WiFi transmit rate and range affected the performance of all routing protocols as shown in Figures 5.18 and 5.19. Increasing the buffer size of mobile nodes will increase the total capacity of the network. A congestion state started when the



(a) Large to small island (LtoS) scenario



(b) Small to large island (StoL) scenario

Figure 5.19: Buffer size and WiFi transmit rate and range increasing impact on the total size of delivered messages TTL 480 min

total size of generated message is 3,276.8 MB while in the original scenario, it is 819.2 MB. Increasing the WiFi transmit rate and range increased the number of messages that can be transferred in a single moment of contact. Figures 5.18(a) and 5.18(b) show the performance of all protocols in TTL 240 min. They achieved almost the same performance from 409.6 MB to 1638.4 MB then in 3,276.8 MB and 6,553.6 MB, SNHDTTL achieved better performance than the other protocols.

Then for TTL 480 min (Figure 5.19(a) and 5.19(b)), the performance of all routing protocols increase compared with TTL 240 min. In both LtoS and StoL scenarios, SNHDTTL achieved better performance compared to the other protocols when the total size of generated messages is 3,276.8 MB or more. Unfortunately in StoL scenario (Figure 5.19(b)), although the total size of generated messages increases twice to 6,553.6 MB the performance of all protocols except EP-TTL decreased.

5.6 Conclusions and Future Work

In this section, we have proposed the spray-and-hop-distance-based with remaining-TTL consideration (SNHD-TTL). This routing protocol integrated three techniques: binary spray, hop distance-based forwarding, and node location dependent remaining-TTL message scheduling, to fit on the island scenario with two message delivery scenarios (i.e., large island to small island, and small island to large island). Global knowledge about statistics obtained from message delivery time is used for TTL-based message scheduling. Applying these combined techniques, we observed that SNHD-TTL outperformed the other evaluated routing protocols. Results also showed that in congested states, a smaller number of message copies was better in the spray phase. Increasing the number of nodes resulted in better performance for all routing protocols due to the capacity of the network (i.e., buffer storage) being increased. It is also suggested that static W and W' values independent of congestion states are not very effective, although appropriate static values showed to work to some extent in our scenarios. In our future work, we aim to develop a way to dynamically learn and estimate W and W' in practical system operation. For scenarios with multiple sources and destinations, we may need to introduce more sophisticated hop distance based forwarding. In addition, we will also consider introducing the network coding techniques as suggested in [27].

Chapter 6

Spray and Hop Distance Routing Protocol in Multiple-island DTN Scenarios

In this chapter, we consider DTN delivery over multiple-island which consists of four islands connected by ferry via station on each island. One source node located in city island, two destination nodes located in the small island, and one island as relay island located among source node and destination nodes. Unnecessary transmission may occur during message delivery i.e., forwarding message to the wrong destination island, which affected the resource consumption (i.e., buffer storage and bandwidth) will be increased. The ferry as a gateway, periodically shuttles among the ferry stations on each island, it affected bottleneck for end-to-end delivery, because it is the only way to convey messages between islands. Further, since the ferry takes a time to make the trip, some messages may expire during the trip.

Considering the above unnecessary transmission and bottleneck, we modified the spray and hop-distance protocol (SNHD) from our previous work [2]. The modification done by adding the decision to reset the limit of message copy (L) based on the location of message to maintain the number of message copy on each island, we use static node (ferry station) to determine the location, for each message arrived at this node, it will reset the L to the initially value. We also increase the restriction of the forwarding decision in hop distance phase to prevent unnecessary transmission during message delivery.

6.1 Adaptive-Spray and Hop Distance Protocol

In order to increase the total size of delivered messages before TTL expiration in the multiple-island scenarios, this Chapter proposes Adaptive-spray and hop distance protocol (A-SnHD) based on our previously developed one, SNHD [2]. A-SnHD switches two phases in each island: the binary spray forwarding and the hop-distance based forwarding. Fig. 6.1 shows the flowchart of the proposed method.

6.1.1 Adaptive-Binary Spray

The binary spray phase is introduced in which a copy limit (L) is defined as the permitted number of message copies for each newly generated messages [8]. An initial value of L is set to each newly generated message at its source node. Assume a message with a copy limit of n ($n > 1$) is stored at a node. When this node encounters another node that does not have (a copy of) this message, copy limit of this message is halved (i.e., $n/2$) and a copy is forwarded to the encountered node. For a message with a copy limit of 1, it switches to the hop distance-based forwarding. In A-SnHD, the value of copy limit of each message will be reset to the initial value when it reaches an ingress point of each island (i.e., ferry station). This adaptive-binary spray can maintain the number of message copies on each island.

6.1.2 Hop Distance-based Forwarding

A message with a copy limit of 1 is managed by the hop distance-based forwarding. In this phase, a message is forwarded to only a node that has a lower hop distance value to the message's destination. Each destination node is stationary and has a hop distance value

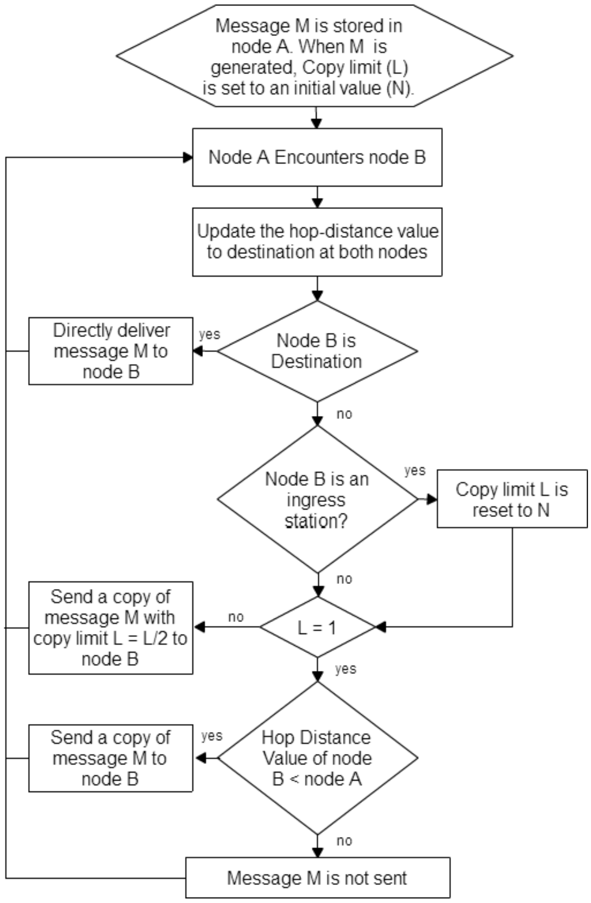


Figure 6.1: Flowchart of the proposed method.

of 0 to itself. When two nodes encounter each other, they will appropriately update their hop distance values (h) to destinations of which at least each of them is aware. A node that periodically encounters the destination directly (i.e., a "good" nearest node) has the smallest h of 1. If a node with h more than 1 encounters such a nearest node, messages are surely forwarded to this nearest node, and those messages will likely be delivered to the destination later; however, a node that encounters the destination once but never goes back again (i.e., a "bad" nearest node) also has h of 1, and thus messages forwarded to such a nearest node will never be delivered to the destination. As a routing decision, this method will help to reduce the unnecessary message transmission (i.e., to another node that has a similar or less

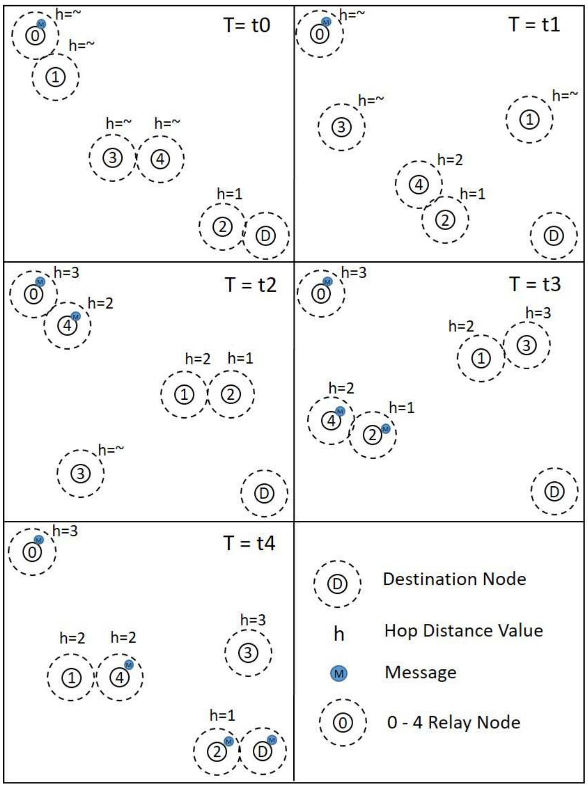


Figure 6.2: Example of process of the hop distance-based forwarding

possibility to reach the destination node and to a wrong island during message delivery).

Figure 6.2 shows a process of the hop distance-based forwarding. Node 0 has a message destined to node D. At $T = t0$, node 2 encounters node D and its h for D is set to 1. The update process of h and message forwarding does not occur when two nodes with $h = \sim$ meet. At $T = t1$, node 4 updates its h for D to $1 + 1 = 2$, meaning one hop distance from node 2. At $T = t2$, after node 0 updates its h value to 3 by adding one to h of node 4, it forwards the message to node 4. At $T = t3$, node 4 forwards the message to node 2 because h of node 2 is lower than that of node 4. At $T = t4$, while node 4 does not forward the message to node 1 with the same h, the node 2 successfully forwards it to the destination D.

6.2 Performance Evaluation

This section analyzes the performance of the proposed A-SnHD routing protocol in comparison with above described routing scheme: Epidemic (EP) as a basic one and PRoPHET-V2 (PV2) as a widely-known sophisticated one. The simulation uses the Opportunistic Network Environment (ONE) simulator [28].

6.2.1 Simulation Scenario

The simulation scenarios use a map-based model of four islands that reflect a real situation in Indonesia. It consists a part of the city of Makassar and three small islands which are located near from the city. We assume a large e-learning content is delivery from source node on the city to two destinations in marginal islands, via the central island which acts as relay island. Cars and buses are employed as relay node for message delivery on each island, and the ferries between islands. A similar type of scenarios can be seen in literature as well. For example, [27] considered segmented island-hopping scenarios where stationary nodes are located in three geographically separated groups that connected by three mobile "traveler nodes".

Six ferry station nodes, two destination nodes, and one source node placed at the map position as shown in Fig. 6.3. During 20 h of simulation time, 97 mobile nodes (e.g. car, bus, and ferry) move on the map road with the warm up time of 30 minutes. The car speed is 10-30 km/h, and bus speed is 5-20 km/h. Cars and buses are moving along the map on each island using car movement model while each ferry node moves according to its route between islands. Note that, as the limitation of ONE simulator, the maximum node buffer size is 2,000 MB. In our scenarios, gateway nodes (ferry stations and ferry itself) need to have a buffer that is about ten times or larger than mobile nodes. So we decide to introduce some scaling in which we select 200 MB buffer for mobile nodes, 2,000 MB for gateway nodes, and set smaller message size and WiFi connection speed with a transmission data rate

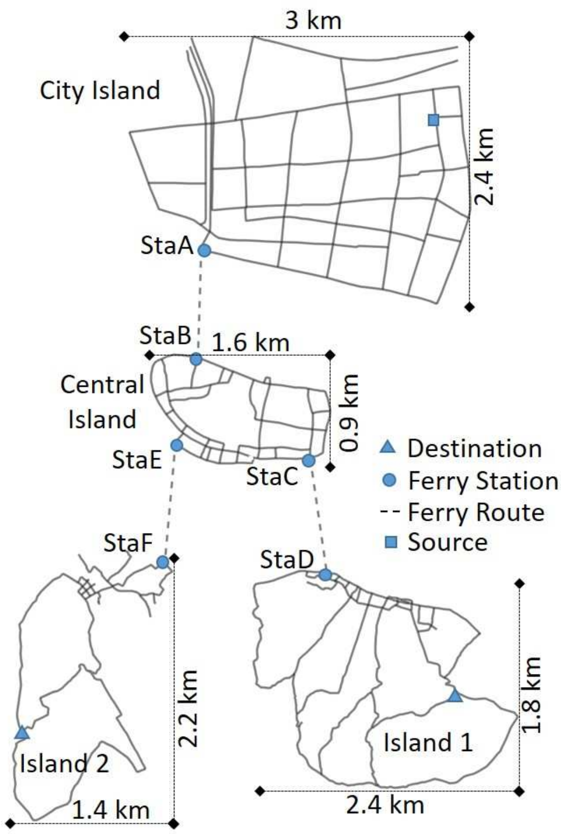


Figure 6.3: Simulation scenario.

of 4.5 Mbps and an omnidirectional transmission range of 30 m as considered in [29]. The traveling time (sailing) of ferry nodes is 15 minutes and waiting time on each island is 30 minutes.

Message are originated depending on the message delivery scenario, there are two message generation scenarios: first, from one source in city island to two destinations node in island 1 and island 2 (1s-to-2d); second, from two sources in island 1 and island 2 to one destination in city island (2s-to-1d). Each source node generates a number of messages to one of destinations. Each message is with size of 0.4 megabytes and time-to-live (TTL) is 12 hours. A larger value of TTL will increase the total size of delivered messages to some

Table 6.1: Simulation parameters

Parameter	Value
Simulation time	20 h
Node buffer size	Mobile = 200 MB
	Stationary = 2,000 MB
Transmission speed	4.5 mbps
Transmission range	30 m
Message TTL	12 h
Node speed	Bus = 5-20 km/h
	Car = 10-30 km/h
Total size of	204.8 MB, 409.6 MB
Generated messages	819.2 MB, 1,638.4 MB,
	and 3,276.8 MB
Message creation duration	8 h
Message size	0.4 MB
Warm up time	30 min
Initial value of L of A-SnHD	3 messages

extent with a longer latency. Since we only focus on message forwarding mechanism, we used default message scheduling policy and message drop policy of the ONE simulator as random and drop oldest, respectively.

All messages are generated randomly and uniformly over 8 hours. We examine five cases of the total size of generated messages; 204.8 MB, 409.6 MB, 819 MB, 1,638.4 MB, and 3,276.8 MB. A large total size implies a high message generation rate (i.e., a high network congestion level). In all simulation scenarios, the configuration of PV2 protocol (P_{ini}, β, and γ) and A-SnHD (copy limit L) have to be defined first. We used the parameters for PV2 as default values: $P_{ini} = 0.5, \beta = 0.9$, and $\gamma = 0.998$, and the initial L value of A-SnHD as 3 messages, later we also evaluate performance of A-SnHD by varying the L value. Details of the simulation parameters are presented in Table 6.1.

6.2.2 Performance Metrics

We use the following three metrics to compare the performance of three routing protocols:

1. *Total Size of Delivered Messages*, the goal of routing development in DTN is to achieve high delivery performance. This metric is the measure of the message size multiplied by the number of messages successfully delivered to the destination before TTL expiration. EP as the simple greedy routing shows the best delivery performance when the network resource is sufficient. However, as the simulation results show, EP is not the best in our resource limited conditions.
2. *Average Latency*, this measure is another important concern in DTN routing evaluation, it represents an average time difference between the message generation time at the source and the message received time at the destination over all successfully delivered messages.
3. *Overhead Ratio*, is defined how many additional copies of messages were relayed for each delivered message, it represents the efficiency of message transmission and desirable to have a low overhead ratio.

6.2.3 Performance Analysis

One source to two destinations (1s-to-2d) scenario

The message is generated from a source node in city island and destined to island 1 and island 2. In simulation, the destination is randomly selected from two when each message is generated. Figure 6.4 shows that A-SnHD achieved the best performance compared with other two especially at a high network congestion level, i.e., when the total size of generated messages is greater or equal to 819.2 MB. The implementation of the probabilistic routing

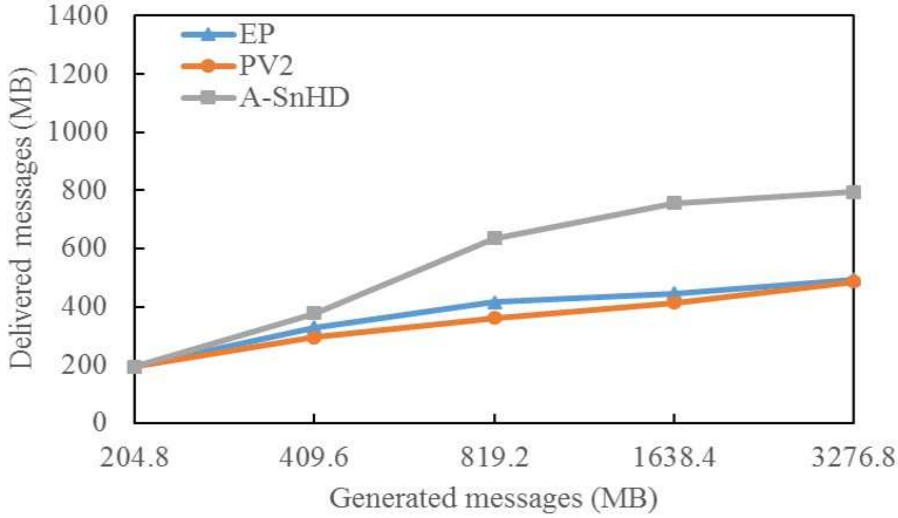


Figure 6.4: Comparison of the total size of delivered messages 1s-to-2d scenario.

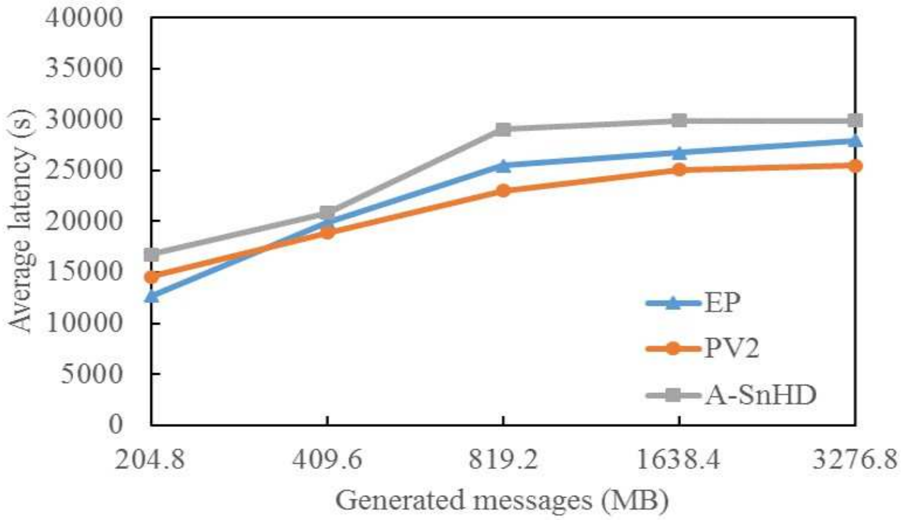


Figure 6.5: Comparison of average latency 1s-to-2d scenario.

protocol using history of encounter as a routing decision in PV2 did not work well at a high network congestion in this scenario.

The limitation of message copies in A-SnHD results that the network can store more

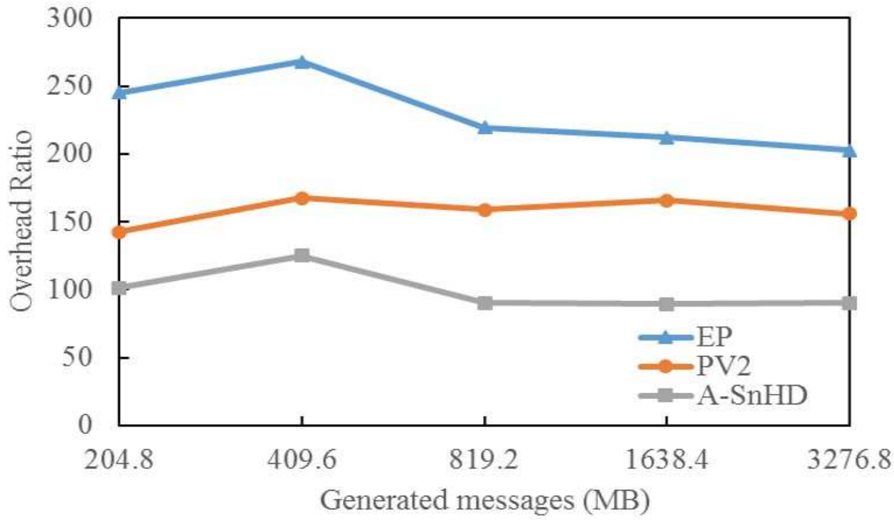


Figure 6.6: Comparison of overhead ratio 1s-to-2d scenario.

different messages. On the other hand, it also results a higher average latency of A-SnHD compared with the other protocols, as illustrated in Figure 6.5. Some messages may be dropped due to buffer full or TTL expiration before it reached the destination node while A-SnHD significantly outperformed other protocols in term of the total size of generated messages.

The limitation of message copies leads to fewer message relay transmissions. The overhead of A-SnHD is lower than that of EP and PV2 as illustrated in Figure 6.6. EP has the higher overhead which may result in a high probability of message dropping in case that the buffer resource is scarce. In all protocols, as the number of generated messages increases, the overhead ratio is almost the same or slightly decreases.

Figures 6.7 and 6.8 show the number of “different” messages delivered to gateway stations and the final destinations 1 and 2 in a single simulation instance as example, in case that the total size of generated messages is 3,276.8 MB. Note that a gateway station may receive a copy of the same message more than once if the old copy is deleted due to buffer full condition; “Different” means we count it only once in such situation. The number of

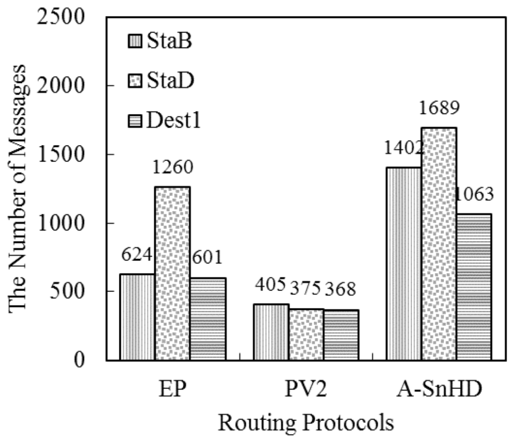


Figure 6.7: The number of messages delivered to gateway stations and the final destination 1 of 1s-to-2d scenario (StaD includes messages to dest 2).

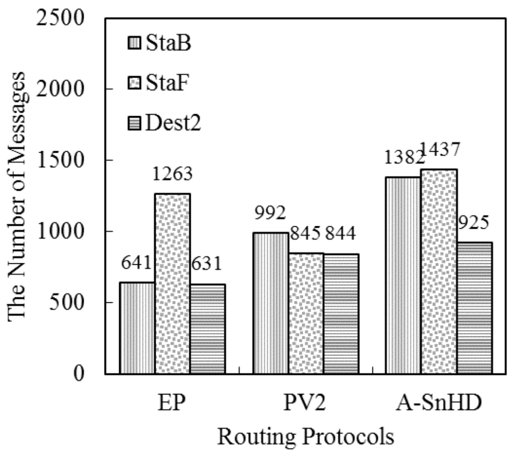


Figure 6.8: the number of messages delivered to gateway stations and the final destination 2 of 1s-to-2d scenario (StaF includes messages to dest 1).

generated messages was about 8000.

These Figures are used to evaluate how many messages are lost in each island and how many messages are forwarded to a wrong island by each protocol. StaB in Figures 6.7 and 6.8 indicates the number of messages delivered to station B (central island) bound for

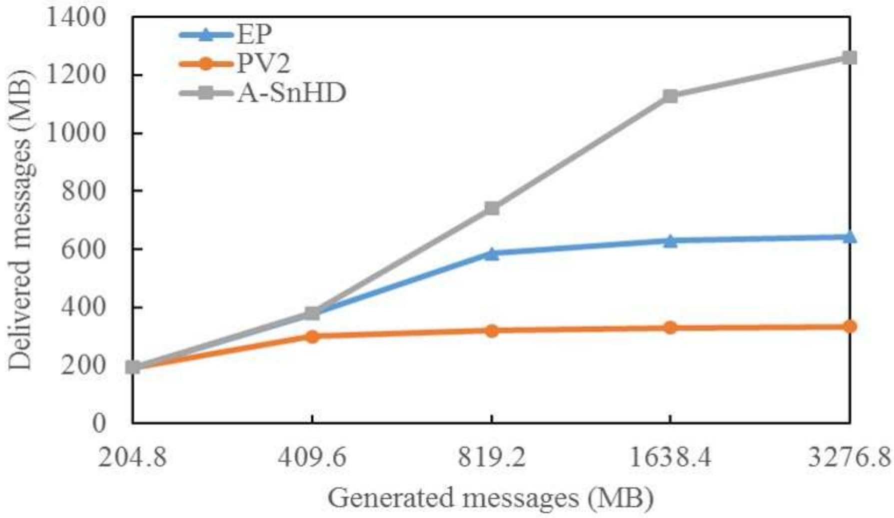


Figure 6.9: Comparison of the total size of delivered messages 2s-to-1d scenario.

Dest1 and Dest2, respectively. StaD indicates the number of messages delivered to station D (island 1) for all destinations (Dest1 + Dest2) and StaF indicates the number of delivered messages to station F (island 2) for all destinations. Comparing StaB for each destination between protocols, it is shown that A-SnHD can deliver a much higher number of messages to station B (1402 for Dest1, 1389 for Dest2 in this example), while EP does deliver only $624 + 641$ messages. This implies EP lost too many generated messages in the source island. Furthermore, in EP, StaD, the number of messages delivered to station D, is almost the sum of StaB with destinations 1 and 2. Since the number of messages from StaB is small enough not to cause network congestion in the central island, EP can just spread almost all messages from StaB to both StaD and StaF regardless of each message's destination.

In contrast, the number of delivered messages of PV2 in StaB is slightly higher than StaD and StaF. PV2 can prevent messages from being forwarded to a wrong island, although its final performance is similar to or lower than EP. On the other hand, the number of delivered messages of A-SnHD in StaD and StaF are larger than in StaB. A-SnHD can forward almost all messages without loss in the central island but some of them are delivered to a wrong

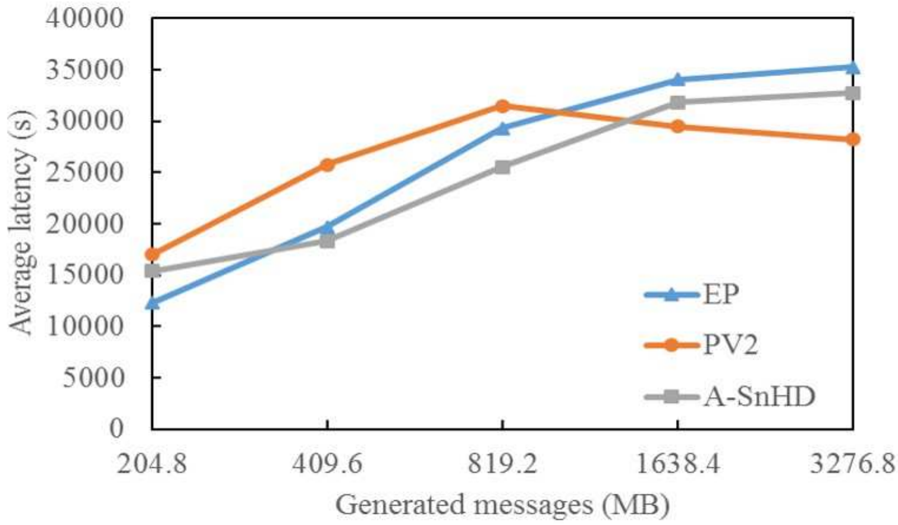


Figure 6.10: Comparison of average latency 2s-to-1d scenario.

island. This is because A-SnHD implements a prevention method for wrong forwarding only in hop-distance based forwarding phase, and some messages arriving at an egress gateway stations still have a copy limit $L > 1$ (i.e., in binary spray phase).

Two sources to one destination (2s-to-1d) scenario

We consider two source nodes located in different islands (island 1 and island 2) and a destination node located in city island. In simulation, the message's source is randomly selected from two when each message is generated. Figures 6.9, 6.10, and 6.11 show the performance of all protocols in 2s-to-1d scenario. In general, EP and A-SnHD achieve better performance in this scenario compared with 1s-to-2d scenario. This is mainly because each source node generates around half of the total number of generated messages, thus the resource (i.e., buffer storage and bandwidth) consumption in each source island is lower than that in 1s-to-2d scenario.

On the total size of delivered messages (Fig. 6.9), A-SnHD achieved the highest performance compared with the other protocols especially at a high congestion level, i.e., when

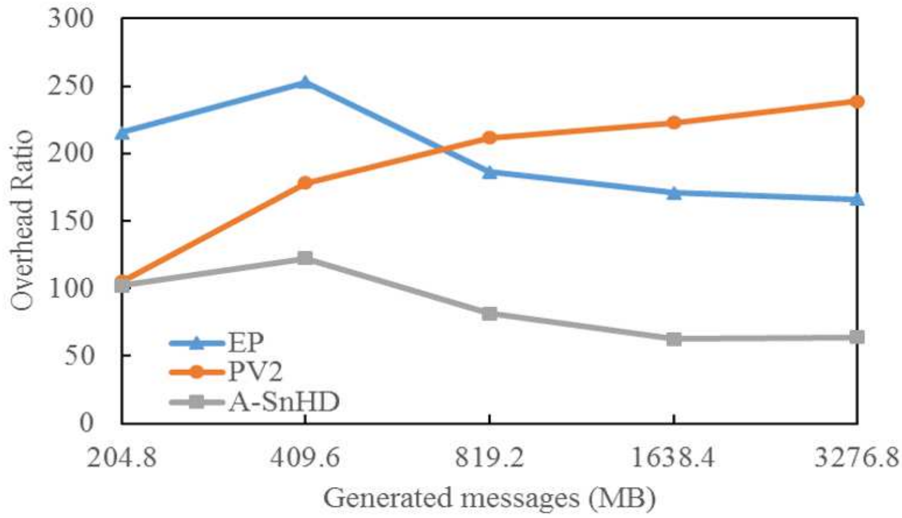


Figure 6.11: Comparison of overhead ratio 2s-to-1d scenario.

the total size of generated message is greater or equal to 819.2 MB. The average latency of all protocols are diverse as the total size of generated message increases (Fig. 6.10). EP has the highest average latency when the total size of generated message is less or equal to 819.2 MB, then PV2 is highest when the total size of generated message is greater or equal to 1638.4 MB. Figure 6.11 shows the overhead ratio of all protocols, A-SnHD achieved the lowest overhead.

Impact of variying L copies on A-SnHD performance

To show the impact of the copy limit L on A-SnHD performance in terms of the total size of delivered messages, we changed the value of L from 3 messages to 5 and 15 messages. In general, a large L value decreases the performance of A-SNHD when the total size of generated message is large as shown in Figures 6.13 and 6.14. When the network capacity is enough, the performance of different L is almost the same. In 1s-to-2d scenario (Figure 6.13), the performance difference between $L = 5$ and $L = 15$ is not so large. On the other hand, for $L = 3$ and $L = 5$, the performance difference becomes large as a congestion state occurs. For

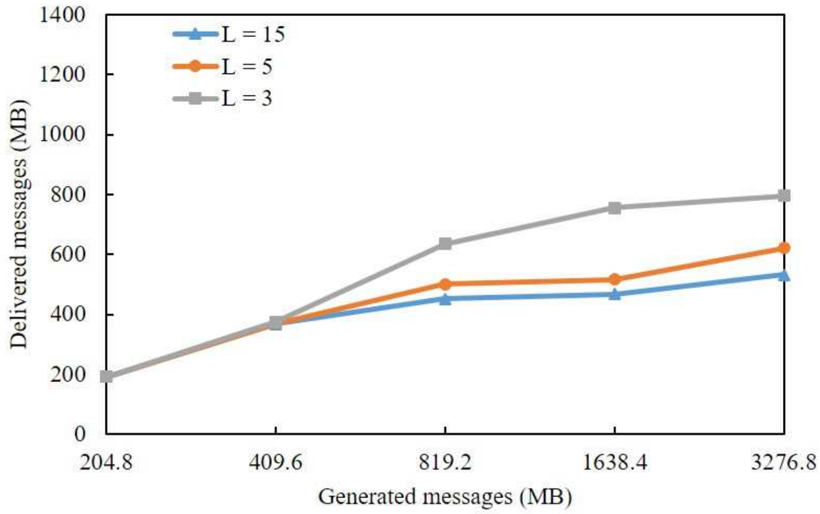


Figure 6.12: Impact of L value on the total size of delivered messages 1s-to-2d scenario

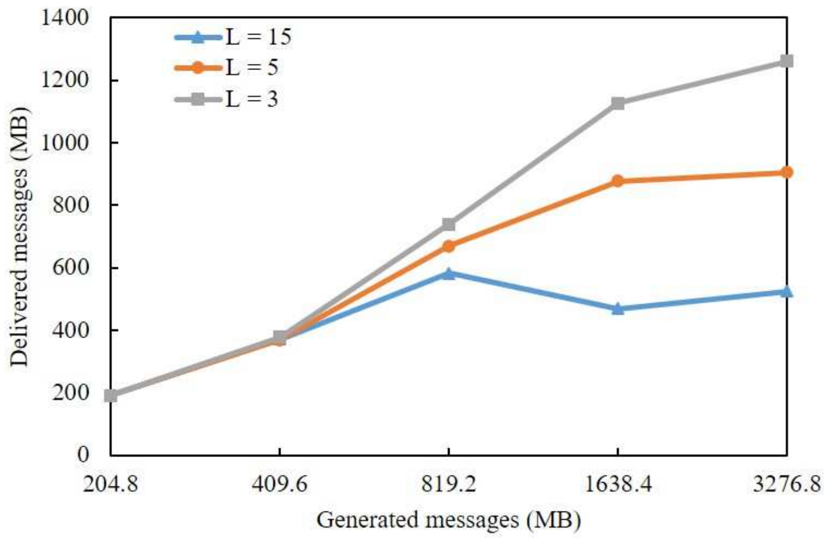


Figure 6.13: Impact of L value on the total size of delivered messages 2s-to-1d scenario

2s-to-1d scenario, the performance differences are larger than in 1s-to-2d scenario (Figure 6.14). $L = 15$ showed a very bad performance compared with the other L values. A too large L allows a message in the spray-phase to reach any ferry station in the central island. Such messages, since the hop-distance forwarding is disabled, will be forwarded to a wrong island.

6.3 Conclusions and Future Work

In this Chapter, we have proposed Adaptive-spray and hop distance-based protocol (A-SnHD), by modifying our previous proposed protocol in [2]. A-SnHD switches two phases in each island: the binary-spray forwarding is used when a message reaches each island for initial dissemination in that island and then the hop distance-based forwarding is used in a strict manner to prevent unnecessary transmission to wrong islands.

Based on the ONE simulator-based evaluation in multiple-island scenarios reflecting a real situation of Indonesia, it has been shown that, while it is simple, A-SnHD increases the total size of delivered messages and at the same time reduces the overhead ratio comparing with EP as a basic protocol and PV2 as a sophisticated protocol. For the future work, finding a better copy limit L in the spray phase should be considered, which can change depending on local information such as island size. We will also investigate a better buffer management by utilizing the information on remaining TTL of each message to mitigate the buffer full condition, which we tried in more simple scenario in our previous work [2].

Chapter 7

Concluding remarks

In this dissertation, we introduced a design for low-cost wireless information networks using existing infrastructure for use in remote or rural areas. Our solutions are case-specific and consider the local conditions and applications. Two technologies were used: (i) stationary multi-hop wireless networking on static facilities and (ii) storecarryforward-based ad-hoc multi-hop wireless networking using vehicle transportation infrastructure.

In Chapter 3, we introduced a framework for message transmission scheduling on a tandem multi-hop transmission model over an existing facility such as electric power transmission towers. Some links are lossy because the existing facility was not constructed to provide relay nodes for wireless multi-hop networking. By applying mathematical optimization, we were able to obtain a static assignment solution for the number of time-slots assigned to each link. In addition, we introduced a simple XOR network coding-based scheme for proactive message transmission using the proposed static time-slot assignment. Simulation results showed that the probability that all messages were successfully delivered to the server (via gateways) using our proposed framework was comparable to and sometimes even better than that achieved by ACK-based reactive recovery schemes, despite these being both more complex and costly. This suggests the effectiveness of our approach that combines static global time-slot assignment to eliminate interference with local message selection for transmission using simple network coding-based proactive message re-transmission to recover lost messages.

In Chapter 4, we analyzed the performance of our DTN routing protocol in an island scenario, wherein a number of messages are generated by a single source node on the main island and delivered to a single destination on a small island, with a message lifetime (TTL) of 2 h. Four routing protocols (Epidemic (EP), MaxProp (MP), PRoPHETv2 (PV2), and Direct Oracle (DO)) were examined by varying the number of created messages (message generation rate), the message size, transmission range, and transmission speed. While our investigation is in the preliminary stage, it has revealed complex dependencies of performance on both the scenario parameters and the routing protocols. This suggests that no single best routing protocol exists. This motivated us to seek an optimal segmentation (message size) for file transfer.

In Chapter 5, we proposed a system called spray-and-hop-distance-based with remaining-TTL consideration (SNHD-TTL). This routing protocol integrated three techniques: binary spray, hop distance-based forwarding, and remaining TTL consideration message scheduling based on global knowledge about the network. In the island case, we considered two message delivery scenarios: a large island to a small island and a small island to a large island. Global knowledge of the statistics obtained from message delivery times is used for TTL-based message scheduling. Applying these combined techniques, we demonstrated that SNHD-TTL outperformed the other evaluated routing protocols. The results also showed that, in congested states, it was better to use a smaller number of message copies in the spray phase. Increasing the number of nodes resulted in better performance for all routing protocols as the capacity of the network (i.e., buffer storage) increased. Moreover, it is suggested that although appropriate static values were shown to have limited success in our scenarios, it is ineffective to use static W and W values independent of congestion states.

In Chapter 6, we proposed the adaptive-spray and hop distance protocol (A-SnHD), a modified version of our previously proposed protocol SNHD [2], which did not work well in a multi-island scenario. A-SnHD has two phases: binary spray with adaptive L copies depending on message location and hop distance-based forwarding. Performance evaluation based on a multi-island scenario in Indonesia demonstrated that our proposed protocol was able to increase the total number of generated messages while imposing a smaller overhead ratio compared with EP and PV2. The performance of all protocols in a 1s-to-2d scenario was lower than that in a 2s-to-1d scenario because of buffer overflow.

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